A miniaturized angularly stable dual-band FSS based on convoluted structure and complementary coupling

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Abstract
A miniaturized dual-band frequency selective surface (FSS) with high angular stability is proposed. The unit cells of the proposed FSS have a convoluted pattern and hexagonal contour, which are arranged into array compactly. The FSS is implemented on single substrate with two metallic layers which has a low profile. The top and bottom patterns are complementary which generate two passbands separated by a transmission zero. A high out-of-band suppression is obtained, and the two bands can be tuned simply and flexibly. The FSS is highly stable with respect to different incident angles and polarizations due to the rotationally symmetric structure. An equivalent circuit model is developed, and a prototype working at 2.15 GHz and 3.8 GHz is fabricated, whose dimension is only 0.05λ0 at the lower band. The simulated results agree with measured results very well.

KEYWORDS
angular stability, complementary structure, dual-passband, frequency selective surface, miniaturization

1 INTRODUCTION

Frequency selective surface (FSS) is composed of massive periodically arranged units, which exhibits bandpass or bandstop characteristic to the incident electromagnetic wave. The performances of FSS depend not only on the frequency, but also on the incident angle and polarization. As an excellent spatial filter, FSS has been widely used in radomes, antenna reflectors, absorbers, RF shields and so on. FSS with multiband performances is highly desirable in modern multi-functional communication systems. Furthermore, practical implementations demand FSS with miniaturized unit so that large number of unit cells can be contained in a limited space.

Several approaches have been proposed to design multiband miniaturized FSS. A multiband FSS based on multi-periodicity combined elements which could be regarded as a fractal was presented in Reference 1. In Reference 2, a new method based on the perturbations of a single-band element was proposed to design multiband FSS providing wide range of band ratio. Multilayer structures were utilized to implement dual-band or tri-band FSS in References 3–6, these designs realized multiple transmission poles and zeros which possess highly-selective feature, however their structures were complicated. In Reference 7, a three-dimensional FSS was proposed to realize two flat passbands with a sharp rejection. Reference 8 proposed a simple design technique for multi-stopband FSS based on multi-resonator structure. Composite element which provides multiple current paths was used to create dual-band or tri-band FSSs in References 9–14, these elements had a convoluted structure so that closely spaced resonances and miniaturization characteristics were obtained, in addition, they also showed good angular and polarization stability. In Reference 15, the concept of complementary FSS stemmed from Babinet’s
principle was proposed, which took advantage of the interaction between complementary layers to generate two passbands. Based on this concept, several dual-band FSSs were proposed in References 16–18, in which lumped components loading\textsuperscript{16} or convoluted structure\textsuperscript{17,18} were employed to obtain miniaturization.

In this article, a miniaturized dual-passband FSS based on complementary structure is proposed. The unit cell of the proposed FSS has a convoluted pattern and hexagonal contour, which can be arranged into array compactly. Due to the rotationally symmetric structure, the FSS shows good angular and polarization stability. Since the two passbands are separated by a transmission zero, the proposed FSS has high out-of-band suppression. Furthermore, the proposed FSS is constructed on a single substrate layer and the two passbands can be tuned independently, which make it easy to design and implement. FSS geometry and equivalent circuit are discussed in Section 2. Section 3 presents simulation results and discussion. Experimental verifications are shown in Section 4, and conclusions are drawn in Section 5.

### 2 FSS GEOMETRY AND EQUIVALENT CIRCUIT

The geometry of the proposed FSS is shown in Figure 1. The unit cell of the FSS is composed of two layers of

![Figure 1](image)

**Figure 1** Geometry of the proposed FSS. (A) Front view. (B) Back view. (C) Side view. (D) 3D view. (E) Array arrangement

### Table 1 The physical and electrical parameters of the designed FSS

| Parameters | Value | Parameters | Value |
|------------|-------|------------|-------|
| $D_1$      | 4.29 mm | $L_1$     | 2.195 nH |
| $D_2$      | 8.43 mm | $L_2$     | 2.613 nH |
| $w$        | 0.2 mm  | $L_3$     | 8.218 nH |
| $s$        | 0.2 mm  | $C_1$     | 0.016 pF |
| $\theta_1/\theta_2/\theta_3$ | 60° | $C_2$     | 1.088 pF |
| $t$        | 0.508 mm | $C_3$     | 0.380 pF |

![Figure 2](image)

**Figure 2** Evolution process of the unit cell of the FSS

![Figure 3](image)

**Figure 3** Equivalent circuit of the proposed FSS

![Figure 4](image)

**Figure 4** $S$-parameters of the proposed FSS obtained from full-wave simulation and equivalent circuit model
metallic pattern separated by a dielectric substrate. The top pattern shown in Figure 1A is complementary to the bottom pattern shown in Figure 1B, which means the conducting part and aperture part on the top and bottom layers are complementary. The two complementary layers couple together and generate two passbands separated by a transmission null. The rotationally symmetric pattern forms a hexagonal contour of the unit, and the units are arranged obliquely as shown in Figure 1E to achieve compactness of the whole FSS.

**FIGURE 5** Simulated transmission coefficients of the proposed FSS under different incident angles for (A) TE and (B) TM waves

**FIGURE 6** Variations of transmission coefficient with (A) the number of convolution turns $N$, (B) width of metallic strip $w$, (C) width of slot $s$, (D) layer offset along x-axis $o$
The evolution process of the unit cell is shown in Figure 2. The unit cell evolves from three pairs of conventional dipoles. Next, the end of each arm is bent to increase the length of the dipole, and then the dipole convolutes inward continually to form a triangular spiral structure. This convoluted structure extends the length of metallic strips and slots between them, which in turn increases the equivalent inductance and capacitance so that miniaturization is achieved. In addition, the distribution of the three pairs of convoluted dipole is rotationally symmetric, and has a hexagonal contour, which allows the units to be arranged compactly to avoid grating lobes. The rotationally symmetric structure, miniaturized unit cell and compact array ensure the angular and polarization stability of the proposed FSS, which enable the FSS to work at large incident angles.

Figure 3 shows the equivalent circuit of the proposed FSS, which consists of two parallel resonant networks representing the top and bottom pattern, respectively. The right network \( (L_3, C_2, C_3) \) is the duality of the left network \( (L_1, L_2, C_1) \) due to the complementarity of the proposed FSS. In the left resonant network, \( L_1 \) represents the inductance of metallic strip and \( C_1 \) represents the capacitance of slot. A series inductor \( L_2 \) is introduced to account for the mutual inductance between adjacent unit cells. The dielectric substrate can be modeled as a transmission line which has been ignored in the equivalent circuit since the thickness of substrate is very small compared to the wavelength. A FSS working at 2.15 GHz and 3.8 GHz is designed by CST Studio Suite, and the geometric parameters are shown in Table 1. The equivalent circuit is simulated by ADS and the values of inductors and capacitors extracted by curve-fitting are also shown in Table 1. S-parameters of the FSS simulated by CST and the equivalent circuit model are shown in Figure 4. It can be seen that the two passbands locate at 2.15 GHz and 3.8 GHz, respectively, and there is a distinct transmission null at 2.8 GHz whose transmission coefficient is less than \(-60\) dB. So two highly selective passbands are obtained and the results of the equivalent circuit model are consistent with the full-wave simulation.

### 3 SIMULATED RESULTS AND DISCUSSION

Figure 5 shows the transmission coefficients of the proposed FSS under different incident angles for TE and TM waves. It is observed that the resonant frequencies deviate within 0.6\% for different incident angles up to 80° for both polarizations, which shows excellent angular stability of the proposed FSS. Furthermore, the passband width decreases with the increasing of incident angle for TE polarization, while it increases with incident angle for...
TM polarization, which is caused by the opposite variation trends of wave impedance for TE and TM waves.

To understand the characteristics of the proposed FSS in more detail, the effects of some key parameters on transmission coefficient are investigated. Figure 6A shows the transmission coefficient varying with the number of convolution turns \( N \). When \( N \) increases, the equivalent inductance and capacitance also increase which leads to smaller resonant frequency. The effects of metallic strip width \( w \) and slot width \( s \) are shown in Figure 6B and C, respectively. Since the equivalent inductance decreases with the increasing of \( w \) and the equivalent capacitance decreases with the increasing of \( s \), so it can be observed that the two resonant frequencies increase with \( w \) and \( s \), and the upper band increases faster. As pointed out in Reference 17, the coupling between the top layer and the bottom layer can be adjusted by layer offset, so that the resonant frequencies can be tuned. An offset \( o \) is introduced on the bottom pattern along \( x \)-axis as shown in Figure 1D, and its effects on transmission coefficient are shown in Figure 6D. It is worth noting that the upper resonant frequency decreases from 3.80 GHz to 3.29 GHz when the offset varies from 0 mm to 1.2 mm, while the lower resonant frequency almost keeps constant. So this parameter can tune the upper band independently without affecting the lower band. Furthermore, since the top and bottom layers interact strongly at the passband, the two passbands can get closer or further apart by changing the separation distance of the top and bottom layers (substrate thickness).

From above discussion, it can be seen that the proposed dual-band FSS can be tuned flexibly and
Comparison with other FSS structures

| Reference | \(\varepsilon_r\) | Dimension (mm) | Thickness (mm) | Angle |
|-----------|-----------------|----------------|----------------|-------|
| 10        | 4.3             | 10.4 (0.088\(\lambda_0\)) | 1.6 (0.013\(\lambda_0\)) | \(\theta: 0^\circ–60^\circ\) |
| 11        | 4.3             | 8.4 (0.065\(\lambda_0\)) | 0.8 (0.006\(\lambda_0\)) | \(\theta: 0^\circ–75^\circ\) |
| 16        | 2.65            | 9.1 (0.062\(\lambda_0\)) | 0.5 (0.0034\(\lambda_0\)) | \(\theta: 0^\circ–40^\circ\) |
| 17        | 2.65            | 10.8 (0.086\(\lambda_0\)) | 1.0 (0.008\(\lambda_0\)) | \(\theta: 0^\circ–30^\circ\) |
| 18        | 3.0             | 6.0 (0.054\(\lambda_0\)) | 0.5 (0.004\(\lambda_0\)) | \(\theta: 0^\circ–60^\circ\) |
| 14        | 2.65            | 6.6 (0.113\(\lambda_0\)) | 1.0 (0.017\(\lambda_0\)) | \(\theta: 0^\circ–60^\circ\) |
| 7         | 3.0             | 12 (0.13\(\lambda_0\)) | 15.8 (0.17\(\lambda_0\)) | \(\theta: 0^\circ–40^\circ\) |
| 6         | 2.65            | 7 (0.23\(\lambda_0\)) | 1.6 (0.047\(\lambda_0\)) | \(\theta: 0^\circ–60^\circ\) |
| Structure proposed | 2.65 | 0.065\(\lambda_0\) | 0.0039\(\lambda_0\) | \(0^\circ–80^\circ\) (simulated) |
|           | 3.0             | 0.058\(\lambda_0\) | 0.0038\(\lambda_0\) | \(0^\circ–60^\circ\) (measured) |
|           | 4.3             | 0.048\(\lambda_0\) | 0.0031\(\lambda_0\) | |
|           | 3.55            | 0.05\(\lambda_0\) | 0.0035\(\lambda_0\) | |

| \(|s|\) | \(|w|\) | \(|N|\) | \(|\varepsilon_r|\) |
|-------|-------|------|-------|
| 4.3   | 0.0027 | 0.508 mm | 3.55 |

Independently. First, choose proper substrate thickness according to the frequency ratio of the two passbands. Then the lower band can be tuned by adjusting \(N\), \(w\), and \(s\). Once the lower band is fixed, the upper band can be tuned independently by changing \(o\).

4 | EXPERIMENTAL RESULTS

A prototype of the proposed FSS containing 30 x 30 unit cells with a dimension of 220 mm x 200 mm is fabricated on the Rogers 4003 dielectric substrate whose dielectric constant is 3.55, loss tangent is 0.0027, and thickness is 0.508 mm. Geometric parameters of the FSS are set as the values in Table 1. Figure 7A shows the schematic diagram of transmission and reflection measurement. The FSS is fixed on a pyramidal absorber screen to minimize diffractions from the edge and is measured using a pair of horn antennas and a Keysight N5235B vector network analyzer. The distance between the horn antenna and the FSS is 1 m to ensure far field condition and plane wave incidence. Fabricated prototype and the measurement setup are shown in Figure 7B. Figure 8 shows the simulated and measured transmission coefficients of the proposed FSS under normal incidence. The FSS exhibits two passbands at 2.15 GHz and 3.8 GHz, and the measured results agree well with the simulated results. The measured insertion losses at the two resonant frequencies are 1.9 dB and 2.8 dB, respectively, which are attributed to dielectric loss and measurement error. Figure 9 presents the measured transmission and reflection coefficients of the FSS under different incident angles up to 60° for TE and TM waves. It can be observed that the center frequencies of the two passbands do not change with incident angle and polarization, which verifies the high stability of the proposed FSS due to its miniaturized and rotationally symmetric structure. It should be mentioned that the maximum incident angle is set to be 80° in the simulation (as shown in Figure 5), however in the experimental measurement, the maximum incident angle is 60° since the incident wave will be blocked by the pyramidal absorber when the incident angle exceeds 60°.

Table 2 shows the comparisons between the proposed FSS and previously reported miniaturized dual-band FSS, in which \(\lambda_0\) refers to the wavelength of the lower resonant frequency. The comparison clearly confirms that the FSS proposed in this study has outstanding performance with respect to the unit size miniaturization and angular stability.

5 | CONCLUSION

In this article, a convoluted miniaturized FSS based on complementary structure is proposed to achieve dual-passband high selectivity performance. The FSS is implemented on single substrate with two metallic layers, which has a low profile and simple structure. Due to the rotationally symmetric pattern, the FSS maintains good stability under different incident angles up to 80° for TE and TM waves. The two passbands can be tuned flexibly by adjusting the number of convolution turns, widths of metallic strip and slot, and layer offset. An accurate equivalent circuit model is developed to investigate the mechanism of the FSS. A prototype working at 2.15 GHz and 3.8 GHz is fabricated, whose dimension is only 0.05\(\lambda_0\) at the lower band. The simulated and measured results are in good agreement.
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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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