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An Outstanding Miniaturized Frequency Selective Surface Based on Convoluted Interwoven Element

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Abstract—Based on convoluted interwoven element, a miniaturized frequency selective surface (FSS) with stable band-stop response is proposed in the paper. By extending the four dipoles into the adjacent elements, the equivalent inductance and capacitance are increased, and therefore the proposed FSS realizes promising miniaturization characteristics. The simulation results indicate that the resonant frequency is 1.19 GHz, and the dimension is only $0.027\lambda_0$. Compared to traditional crossed elements, the size is reduced by 94.6%. Besides, the FSS has excellent angle-stability under both TE and TM waves. Finally, the proposed FSS is fabricated and measured, and the experiment results prove the satisfactory consistency with the simulation results.

1. INTRODUCTION

Frequency selective surfaces (FSSs) are usually two-dimensional periodic arrays constructed from metallic patterns [1]. Substantially FSSs are spatial filters, and the object that FSSs reflect or transmit is electromagnetic wave [2, 3]. Generally, FSSs can be divided into patch and slot arrays. The patch arrays can totally reflect electromagnetic wave in the operating band, and the slot arrays do just the opposite [4, 5].

The research of FSSs began in the 1960s [1]. In that time, FSSs were just applied to RCS reduction in military domain [6]. But in recent years, FSSs have been investigated intensively. Many new applications have been found, such as dichroic subreflector, electromagnetic shield in wireless communication system, and microwave polarization rotator [7]. However, for traditional FSSs, the size is about half a wavelength of the operating frequency, which will move the grating region close to the operating band [8]. Besides, it will become difficult to contain enough elements to act as infinite FSSs that have stable to incident wave [9, 10]. To address the problem, a new class of FSSs called miniaturized-element FSSs were developed [11].

In recent years, many effective methods have been proposed to realize FSS miniaturization. In paper [12], a biological structure is proposed to design miniaturized FSS. Moreover, the FSS based on the coupling mechanism between a capacitive surface and an inductive surface in [13] is designed to realize miniaturization characteristics. A 2.5-dimension structure was suggested in [14], which enhanced the capacitance and inductance of the FSS element. Besides, loading capacitor was used to miniaturize the resonant frequency and achieve miniaturization characteristics [15].

In this paper, based on convoluted interwoven element, a miniaturized FSS with stable band-stop response is proposed. Compared with previous miniaturized FSSs, the proposed FSS has superior miniaturization performance. The size is just $0.027\lambda_0$, where λ_0 represents the free-space wavelength of resonant frequency. Moreover, the FSS shows excellent stability for different polarizations and incidences. A prototype is fabricated, and the experiment results are in good agreement with the simulation ones.

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2. FSS DESIGN AND ANALYSIS

To design miniaturized band-reject FSS, a traditional crossed element was considered. According to MUNK theory [1], the size of a traditional crossed element is almost half a wavelength of the operating frequency. In order to realize better miniaturization performance, four dipoles are extended inwardly. Further, the four dipoles are bended and convoluted into adjacent unit cells. The procedure is indicated in Fig. 1. The structure is presented in Fig. 2. The red parts are patch, and the blue parts are FR4 with ε_r of 4.3 and loss tangent δ of 0.025.

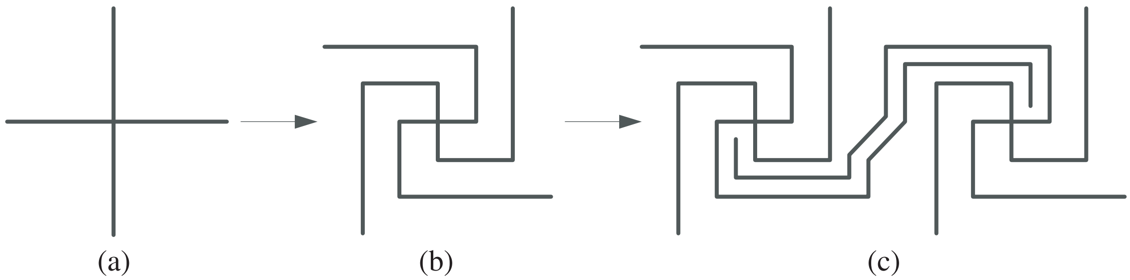


Figure 1. The procedure of design. (a) Traditional crossed element. (b) Un-interwoven convoluted element. (c) Interwoven convoluted element.

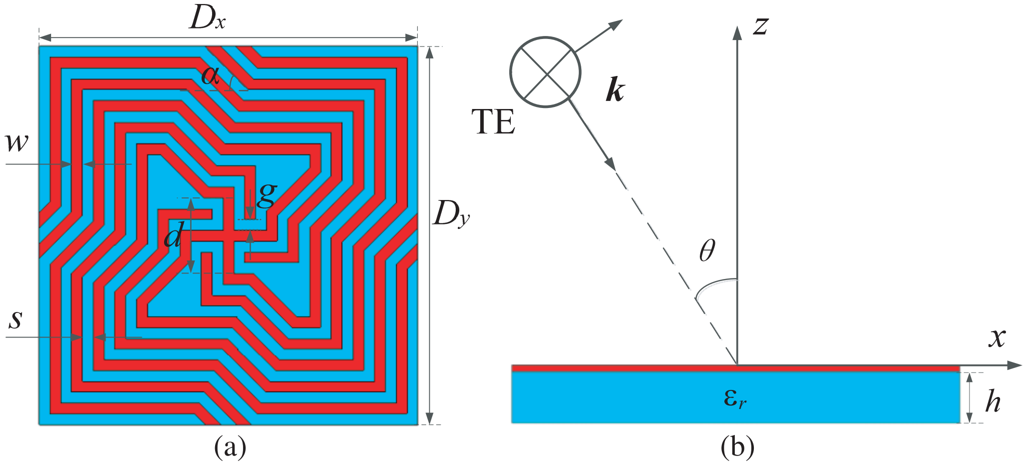


Figure 2. The structure of FSS element. (a) Top view. (b) Side view.

To obtain optimized parameters, Microwave CST STUDIO SUITE is used to simulate the transmission and reflection properties of FSS when being illuminated by plane wave at normal incidence. Following a heuristic process, the optimized parameters are given in Table 1, and the transmission and reflection properties of FSS are given in Fig. 3.

Table 1. Unit-cell dimension.

Parameter	Value/(mm)	Parameter	Value/(mm)
D_x	7	D_y	7
s	0.2	w	0.2
α	40°	h	0.8
d	1.4	g	0.2

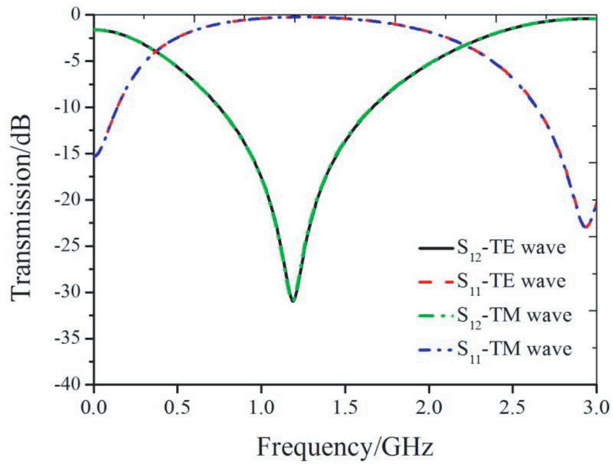


Figure 3. Transmission and reflection properties of proposed FSS.

From Fig. 3, it is obvious that the operating frequency of both polarizations is 1.19 GHz. Since the length of the unit cell is 7 mm, the size of the proposed FSS is only $0.027\lambda_0$, where λ_0 is the free-space wavelength responding to operating frequency. Compared to a traditional crossed element, the size reduction of 94.6% is realized.

To realize a high value of practical application, the FSS should be stable with respect to waves of different incident angles and polarizations. The proposed FSS illuminated by TE and TM waves with the incident angle changing from 0° to 60° is simulated by CST, and the simulation results are given in Fig. 4.

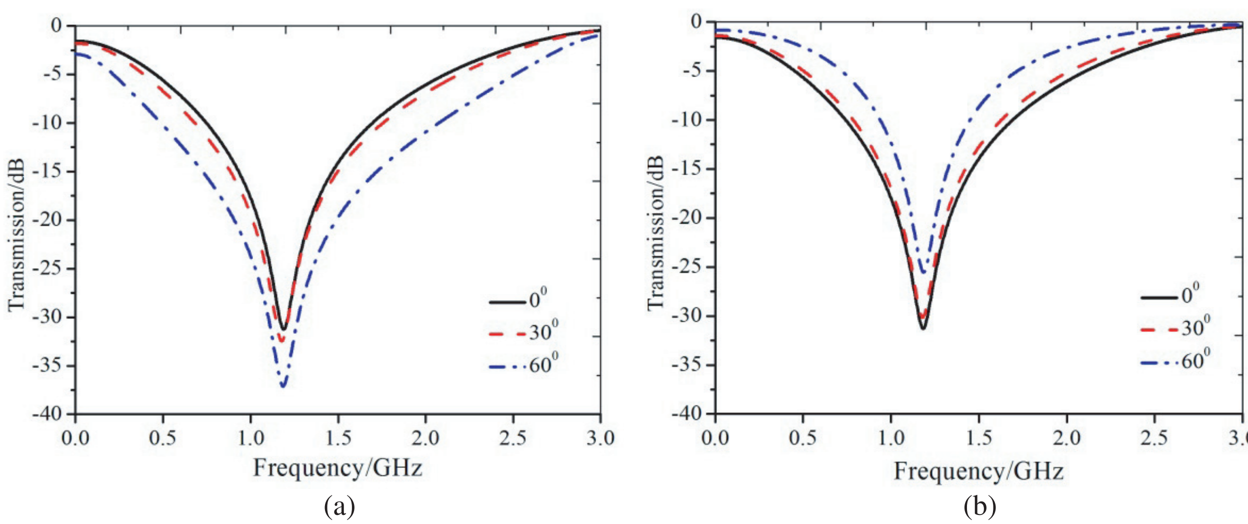


Figure 4. Transmission properties of FSS for (a) TE and (b) TM wave of different incident angles.

As shown in Fig. 4(a), when FSS is illuminated by TE wave, the maximum deviation amount is about 0.93%, appearing in the angle of 60°. In Fig. 4(b), the maximum deviation amount is about 1.26%, appearing when the incident angle is 60°. Hence, the proposed FSS has excellent stability for different incident angles and polarizations.

To explore the miniaturization mechanism of the FSS, TE wave is used to illuminate the arrays in normal incidence. The distributions of surface currents in un-interwoven FSS and interwoven FSS along with relevant equivalent circuit are given in Fig. 5. The left diagram represents the current distribution

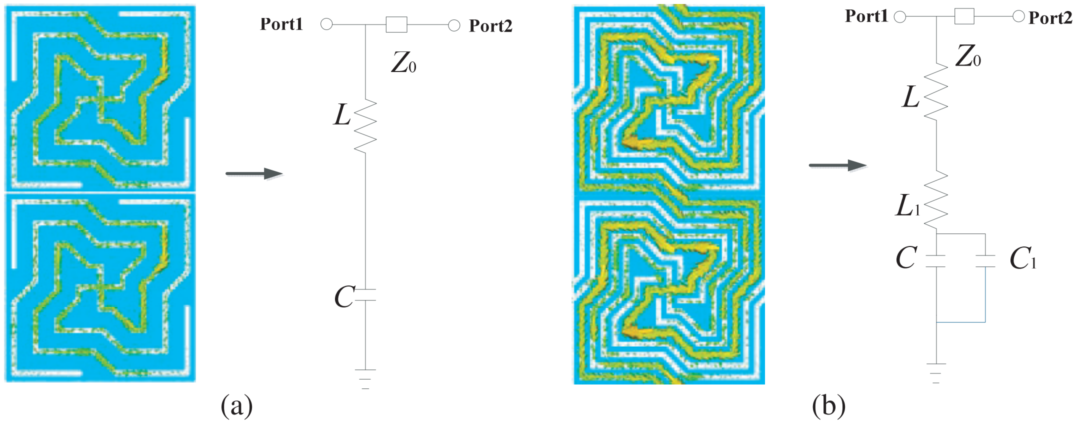


Figure 5. The current distributions and relevant equivalent circuits of two structures: (a) Un-interwoven FSS and (b) interwoven FSS.

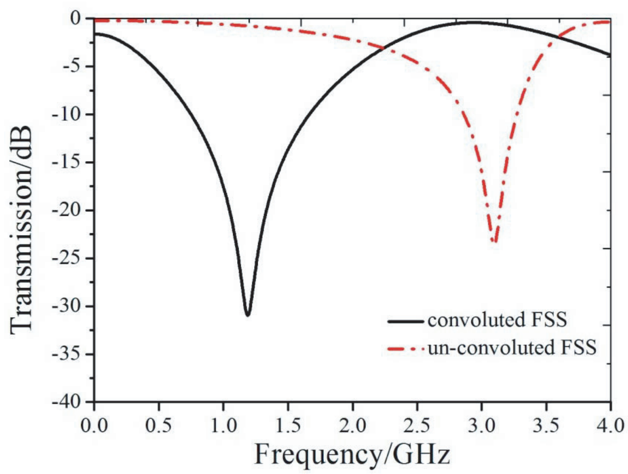


Figure 6. The comparison of transmission parameters in the normal illuminated by TE wave.

at the resonant frequency 3.09 GHz, and the right diagram represents the current distribution at the resonant frequency 1.19 GHz. Besides, the comparison of transmission parameters in the normal illuminated by TE wave is represented in Fig. 6.

According to transmission line theory, band-stop FSS can be modeled as a serial LC circuit when it is illuminated by electromagnetic wave. The resonant frequency is $f = 1/2\pi(LC)^{1/2}$. L represents the inductance of metallic strip, and its value is proportional to the length of the metal strips. C represents the capacitance of spiral slot dipoles, and its value is inversely proportional to the width of the spacing distance between two neighboring strips. Fig. 5 shows that compared with un-interwoven FSS, an additional inductance L_1 and capacitance C_1 are added in the equivalent circuit of interwoven FSS. The series inductance L_1 is used to represent the additional length of the strips, and the parallel capacitance C_1 is used to describe the decrease of the spacing distance between two neighboring strips. In the equivalent circuit, Z_0 is the characteristic impedance of the dielectric substrate. Hence, The resonant frequency of the proposed FSS can be expressed as

$$f = 1/2\pi[(L + L_1) \times (C + C_1)]^{1/2}$$

From Fig. 6, it is evident that the resonant frequency of interwoven FSS is lower than un-interwoven FSS. The diagram validates the analysis.

Based on the above analysis, it is easy to find that the length (L) of convoluted meander strips directly determines the equivalent inductance of relevant equivalent circuit. To further investigate

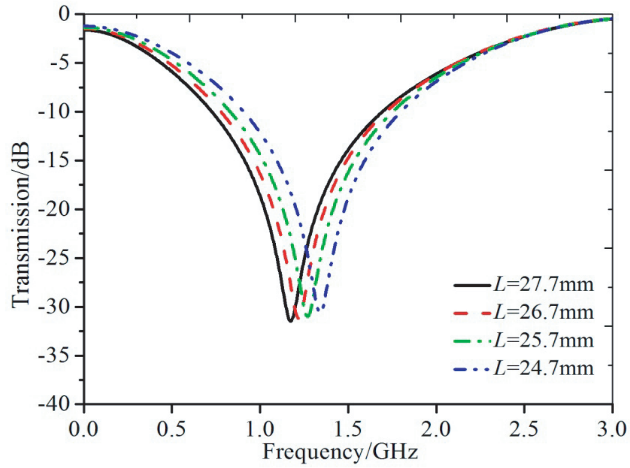


Figure 7. Transmission characteristics of FSS for different parameters L.

the effect of different parameters L on the frequency response of proposed FSS, the transmission characteristics of different parameters L for TE plane wave are given in Fig. 7.

It can be observed that the resonant frequency is increased obviously with the decrease of length L. Therefore, the length of convoluted meander strips should be designed to guarantee the miniaturization of the proposed FSS. In the paper, the length of the convoluted meander strips is 27.7 mm.

To further prove the excellent miniaturization of the proposed FSS, a dimension comparison between proposed FSS and other FSSs in previous papers is represented in Table 2.

Table 2. Comparison of FSS element size.

FSS element	Dielectric constant	Resonant frequency	Size
Ref. [2]	2.65	4.02 GHz	0.058λ
This FSS	2.65	1.4 GHz	0.033λ
Ref. [12]	2.65	3.9 GHz	0.11λ
This FSS	2.65	1.4 GHz	0.033λ
Ref. [13]	2.85	1.48 GHz	0.11λ
This FSS	2.85	0.13 GHz	0.032λ
Ref. [14]	4.4	1.89 GHz	0.062λ
This FSS	4.4	1.55 GHz	0.027λ
Ref. [15]	4.9	3.2 GHz	0.53λ
This FSS	4.9	1.11 GHz	0.26λ

3. EXPERIMENTAL RESULTS

In the paper, the designed FSS is fabricated on FR4 with thickness 0.8 mm having elements of 35×35. The dimension of the FSS is 24.5 cm $\times$ 24.5 cm. The actual version of the structure is shown in Fig. 8. The experiment is carried out in an anechoic chamber. The measurement fixture is shown in Fig. 9. In the experiment progress, Agilent N5230A network analyzer is used to analyze signal wave.

The measured and simulated transmission characteristics for different incident angles varying from 0° to 60° are given in Fig. 10. It is shown that the measured results are in good agreement with simulated ones. The small deviation may come from the processing error and unsteady test condition.

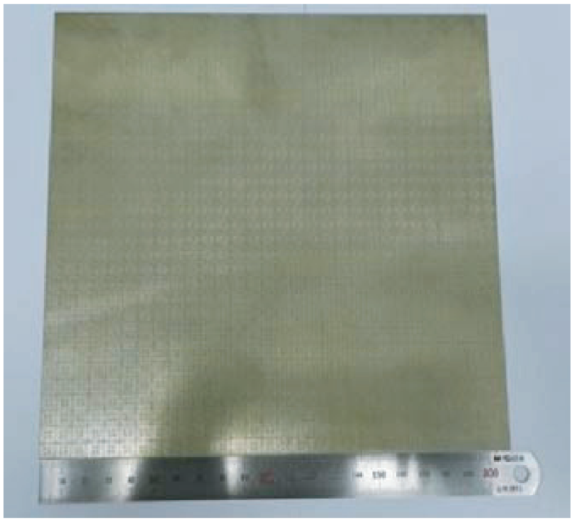


Figure 8. The actual version of fabricated FSS.

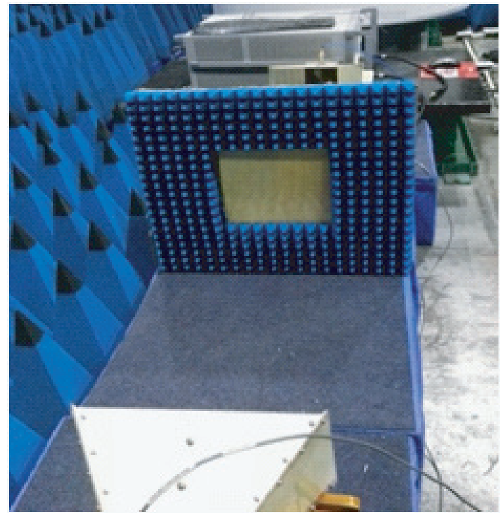
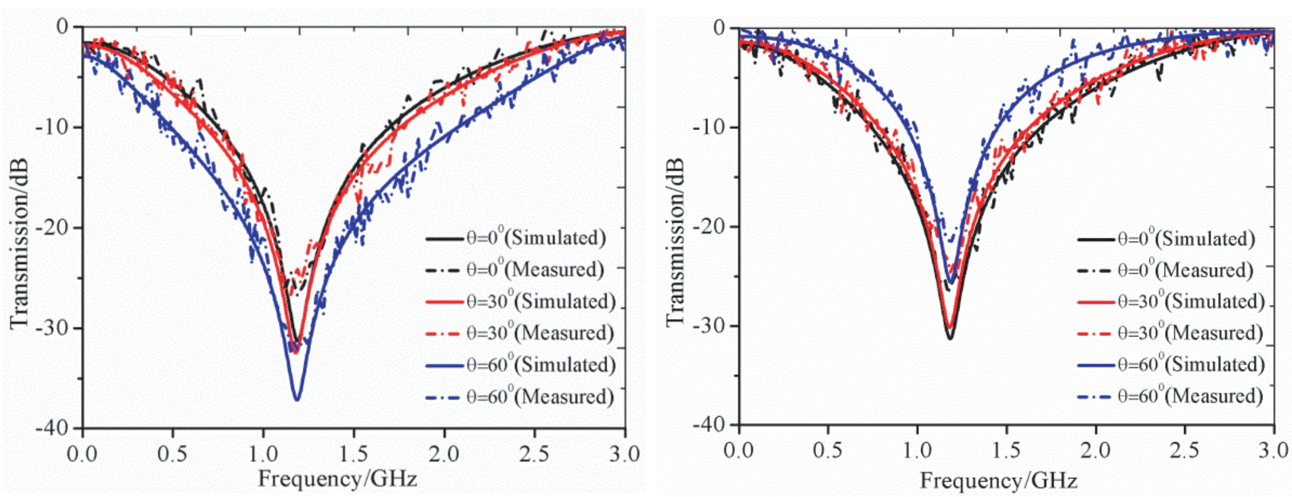


Figure 9. Measurement fixture.



(a) (b)

Figure 10. Measured and simulated transmission characteristics for different incident angles. (a) TE polarization. (b) TM polarization.

4. CONCLUSION

In the paper, based on convoluted interwoven element, a miniaturized frequency selective surface with stable band-stop response is proposed. The simulation results indicate that the central resonant frequency is 1.19 GHz. Since the length of the unit cell is 7 mm, the size is just 0.027λ. Besides, it has excellent stability with respect to different incident angles and polarizations. The structure is fabricated, and the experiment results prove the accuracy of the simulation. Moreover, the proposed FSS has huge value of reference and application in communication fields.

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