

Study on Ultra-Wide Stopband Miniaturized Multilayer Frequency Selective Surface with Capacitive Loading

Guangming Zheng^{1, *}, Cuilin Zhong², Liang Tang³, Peng Luo⁴, and Yan Wang¹

Abstract—In this paper, a novel miniaturized frequency selective surface (MFSS) with capacitive loading is proposed; it has characteristics of low profile, second-order, wide-band, and remarkable wide stopband properties. In a specific frequency band, the proposed MFSS has a second order filter function characteristic. The proposed MFSS is composed of three metallic layers separated by two dielectric substrates, which offers the spatial form of the second order microwave filter. The band and operating frequency can be controlled by the thickness of dielectric substrates and the gaps between the capacitive loading structures. The element size is smaller than $0.05\lambda \times 0.05\lambda$. The element thickness is less than $\lambda/30$, where λ is the free space wavelength at the resonant frequency. The frequency response produced by the proposed MFSS had very good stability when the plane wave incidence angles varied from 0 to 60 degrees. The fundamental frequency f_0 is 2.45 GHz; the relative bandwidth δ is 10%; and the stopband is from 3 GHz to 39.6 GHz. The frequency response demonstrates the excellent filtering performance.

1. INTRODUCTION

Various frequency selective surfaces (FSSs) have been designed for aperture phase correction, beam steering of antennas [1–4], and bandwidth improvement of aperture antennas [5]. FSSs were widely used in radar, communication, electronic countermeasure, invisible electromagnetic field and engineering domain to produce radomes, especially for applications in warships, fighter planes, satellites, etc.

The idea of miniaturized element FSS [5] and its ramification [6, 7] were suggested using rectangle or annular loops, multipoles, rectangle or annular patches, replacing the larger traditional elements. As an obvious difference, these proposed miniaturized element FSSs can very easily get larger number of elements in a finite space to act as an infinite FSS. In order to be more functional, various miniaturized element FSSs were suggested in [8–11]. However, these FSSs had a narrow band and stopband.

A new miniaturized periodic element aiming for producing a controllable band FSS with an ultra-wide stopband is proposed in this paper, which has many virtues such as very small size, low insertion loss, controllable bandwidth, and an ultra-wide stopband. The principles for the element construction and resonances are displayed in detail. New ways are proposed to reduce the element size further. While reducing the element size in a new way, the ultra-wide stopband and passband frequency responses can be gained. The fine frequency response stability is the characteristic of the capacitive loading miniaturized MFSS even for plane wave incidence at different angles.

For further elaboration, the prototype of the capacitive loading miniaturized MFSS was machined and measured. The simulation results are consistent with the measurement ones, which shows the promised performance of the capacitance loading miniaturized MFSS.

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* Corresponding author: Guangming Zheng (2023871894@qq.com).

¹ School of Electronics Engineering of Xi'an University of Posts & Telecommunications, Xi'an 710121, China. ² Shenzhen Jiangbo Chuangxing Electronic Technology Co., Ltd., Shenzhen 518109, China. ³ Shanghai Aerospace Systems Engineering Institute, Shanghai 201108, China. ⁴ Shanghai Aerospace Electronic Communication Equipment Research Institute, 201108, China.

2. MINIATURIZED-ELEMENT FSS AND ITS PERFORMANCE

The capacitive loading is shown in Fig. 1. The lumped parameter capacitance is shown in Fig. 1(a), and the interdigital capacitor is shown in Fig. 1(b). The interdigital capacitor in Fig. 1(b) has the same capacitance as the lumped parameter capacitance in Fig. 1(a).

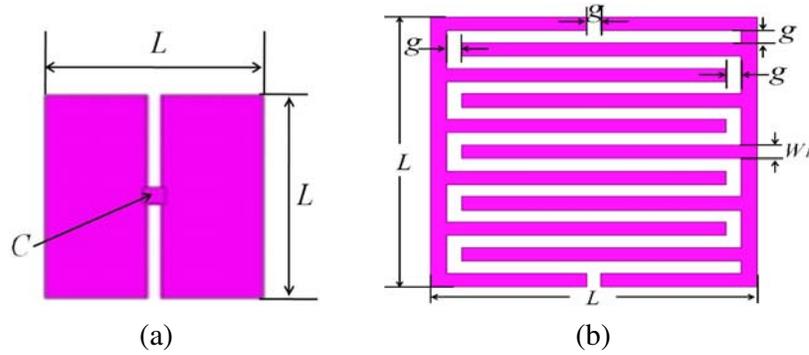


Figure 1. Capacitive loading.

The composition of the newly proposed capacitive loading miniaturized MFSS with an ultra-wide stopband is a three metallic layer PCB, which consists of three metallic layers patches printed on two equal substrate layers.

The composition of the top and bottom metallic layers is shown in Fig. 1, and the equivalent circuit of the top and bottom metallic layers is shown in Fig. 2. The composition of the middle metallic layer is shown in Fig. 3, and the equivalent circuit of the middle metallic layer is shown in Fig. 4. L is the length of the metallic layer in Fig. 1 and Fig. 3, and W is the width of the middle metallic layer in Fig. 3. The bottom and top metallic layers consist of two equal metallic layers in Fig. 1(a) with a gap between two equal metallic layers and capacitors, and in Fig. 1(b) with interdigital figures of width W_1 and gaps g . The structure of the proposed capacitive loading miniaturized MFSS is shown in Fig. 5, which consists of a bottom metallic layer, a top metallic layer, a medium metallic layer, and two dielectric substrate layers.

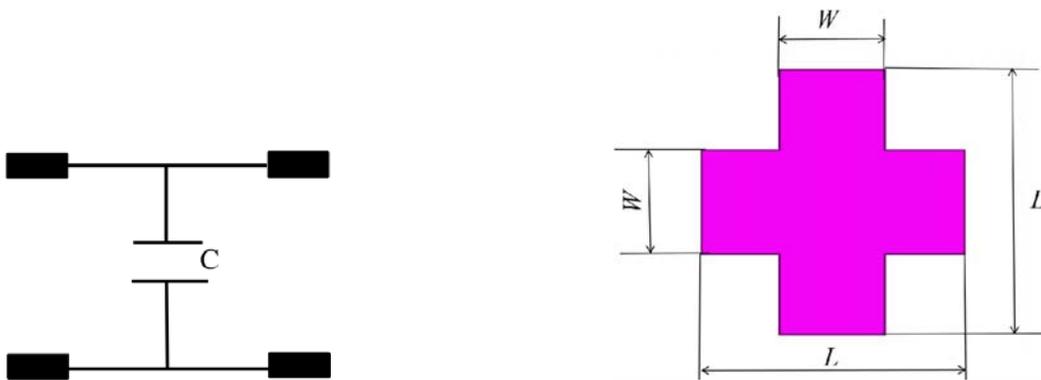


Figure 2. The equivalent circuit of the capacitive loading.

Figure 3. Middle metallic layer.

Study on the wide stop-band MFSS equivalent circuit model is based on a laminated microstrip line and SIR [12–14], the FSS cascading [15]. As shown in Fig. 5, a three dimensional (3D) wide resistance is proposed. With the FSSs equivalent circuit model, the high and low impedance transmission lines and inductors in the model constitute the inductive loaded SIR, and the equivalent circuit is shown in Fig. 6. The equivalent circuit is cascaded by a second order band-pass filter and a third order low pass filter, and shows a wide passband and an ultra-wide stopband filter frequency response [16, 17].

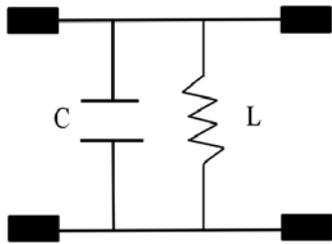


Figure 4. The equivalent circuit of middle metallic layer.

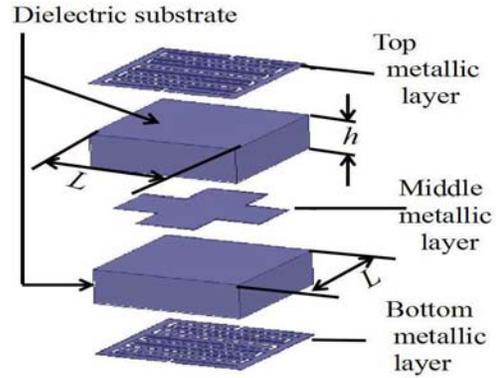


Figure 5. Geometry of the proposed miniaturized MFSS.

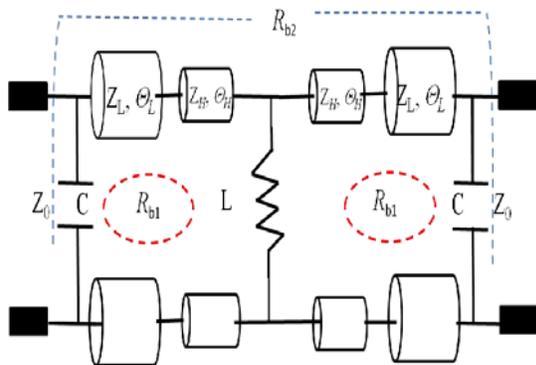


Figure 6. The equivalent circuit of the proposed miniaturized MFSS.

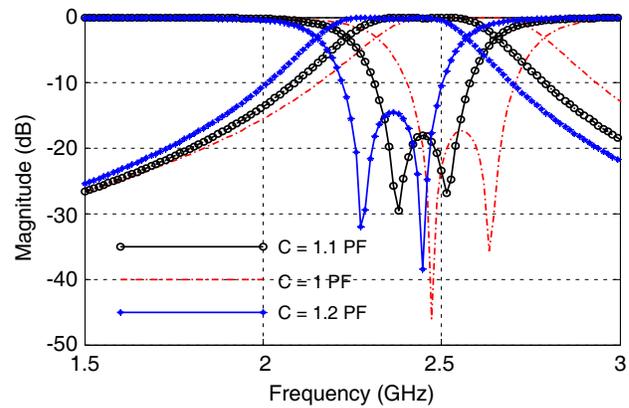


Figure 7. Response illuminated by a normally incident plane wave with the capacitor c as parameter.

The thickness of each substrate layer h is 2 mm, and the width and length of substrate layer L are 6 mm in Fig. 5, respectively, and the thickness of metal layers is 0.018 mm. For demonstration, an ultra-wide stopband FSS using the element shown in Fig. 5 is fabricated on an FR4 substrate with a dielectric constant of 3.2 and loss tangent of 0.0025. The FSS performance is analyzed and optimized by HFSS15 software.

Figure 7 shows the frequency responses of the miniaturized MFSS illuminated by a normally incident plane wave with the value of loading capacitor C as a parameter, and the values of C are 1.2 pF, 1.1 pF, 1.0 pF, respectively. From Fig. 7 we can see that the response frequency changes little as C is varied, which shows a stable frequency response.

Figure 8 shows the frequency responses of the miniaturized MFSS element illuminated by a normally incident plane wave with the value of interdigital fingers as a parameter. W_1 and g are 0.37 mm and 0.197 mm; W_1 and g are 0.361 mm and 0.203 mm; and W_1 and g are 0.36 mm and 0.204 mm, respectively. From Fig. 8 we can see that the frequency response changes little as W_1 and g are varied, which shows a stable frequency response.

Figures 9 and 10 show the transmission and reflection when the capacitive loading miniaturized MFSS is illuminated by an obliquely incident plane wave. Fig. 9 shows the results with an incident plane wave on the lumped parameter capacitance, and Fig. 10 shows the results with an incident plane wave on the interdigital capacitance. As shown in Fig. 9 and Fig. 10, the miniaturized MFSS has very good stable frequency response, as various incidence angles vary from 0° to 60° . The frequency shift is still smaller than 1% of the corresponding resonant frequency. From the frequency response shown in Fig. 7,

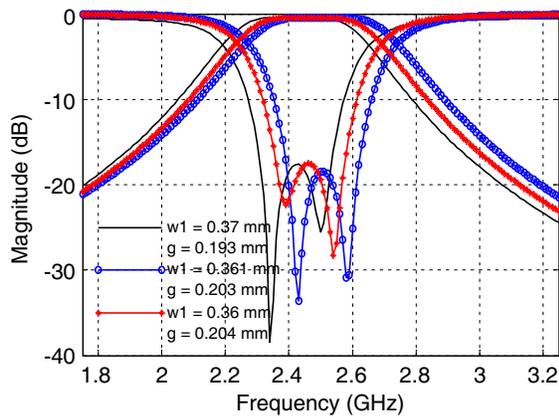


Figure 8. Response curve illuminated by a normally incident plane wave with the interdigital as parameter.

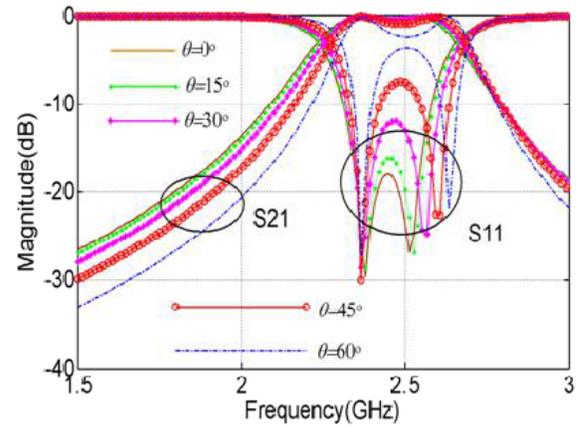


Figure 9. Response curve illuminated by an obliquely incident plane wave on lumped parameter capacitance.

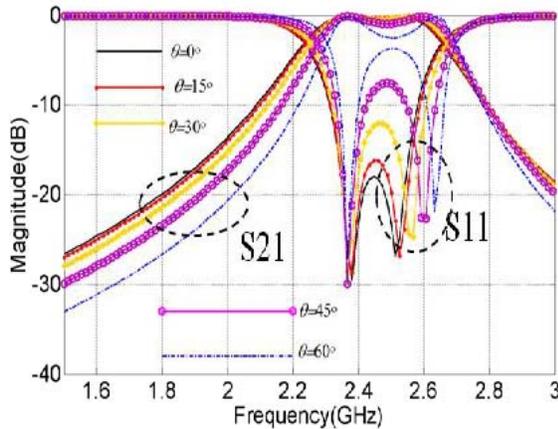


Figure 10. Frequency curve illuminated by an obliquely incident plane wave on interdigital capacitance.

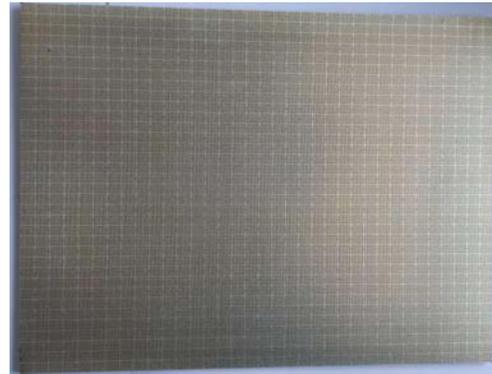


Figure 11. Photographs of the MFSS prototype and element unit.

Fig. 8, Fig. 9, and Fig. 10, we can deduce that the value of capacitor in the equivalent circuit in Fig. 2 is about 1.2 pF.

The symmetry structure of the miniaturized MFSS reduces the sensitivity to different incidences. The center frequency and band can be controlled by adjusting the value of capacitive loading such as gaps, width, capacitor, and length of the figures. In the center of the element, there is capacitive loading. The capacitive loading reduces the miniaturized MFSS size, realizes the low frequency response, and realizes stable angles response.

Physically, the capacitive loading in each pattern of the element behaves as a monopole, which determines its corresponding resonant frequency. The resonance frequency is decided by capacitance loading. In order to reduce the MFSS size and get low frequency response, the capacitive loading is intentionally added.

A prototype of the proposed MFSS filter has been fabricated and tested to validate the design method. The fabricated MFSS is shown in Fig. 11. The size of the MFSS prototype is 240 mm \times 240 mm. It consists of 40 \times 40 elements. A KEYSIGHT vector network analyzer and two horn antennas were used for the measurement. Each horn antenna which has 20 dB gain and -20 dB return loss is placed 200 cm away from the MFSS. The distance is large enough to satisfy the far-field condition. Thus, the

wave arriving at the MFSS can be considered as a plane wave. In order to avoid spillover at the edge of the MFSS, RF absorbing materials were used around the edges.

We tested transmission and reflection twice: with and without the MFSS presented, to the calibration. The return loss S_{11} and transmission coefficient S_{21} were tested at various angles of incidence. The measured results are shown in Fig. 12 and Fig. 13 for incident angles of 0° . As can be observed from Fig. 12, the MFSS structure exhibits a band-pass, and the center frequency of the pass-band is 2.45 GHz with a relative bandwidth of 10%. Fig. 13 shows clearly that the tested stopband of the miniaturized MFSS extends to 39.6 GHz with a rejection level of 15 dB, and from 3 GHz to 15 GHz the rejection level is 30 dB. The harmonic frequency of the proposed miniaturized MFSS exceeded 16 times of the fundamental frequency f_0 . The simulation results are consistent with the tested ones and fully prove the accuracy.

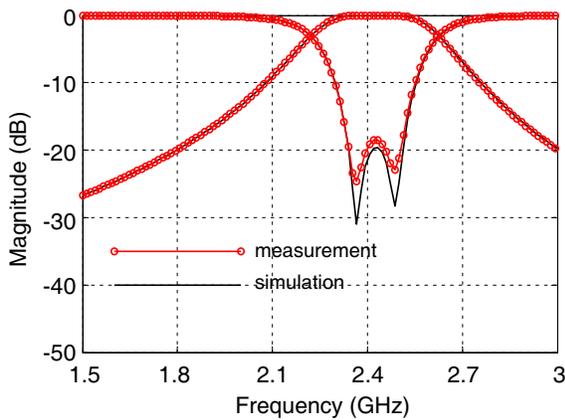


Figure 12. Narrow band responses.

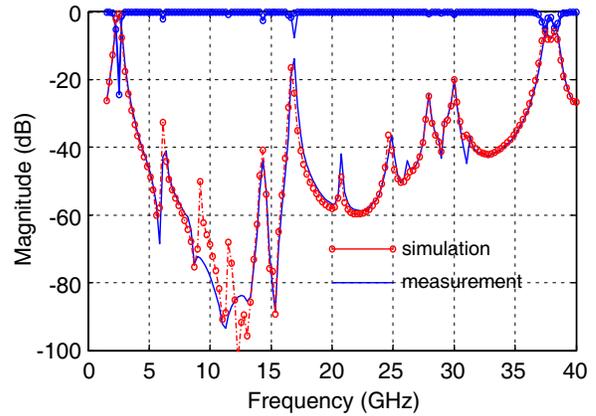


Figure 13. Wide band responses.

A comparison of the proposed MFSS with other reported ones is illustrated in Table 1. It can be seen that the proposed MFSS has the smallest element size and the only ultra-wide stopband. The overall thickness is one of the lowest as well. The thickness is only slightly thicker than that in [11]. However, the fractional bandwidth is about half. This is because to design an MFSS with a wider band, the coupling between the resonant layers required needs to be stronger. Hence, the substrate could be thinner or with high dielectric constant.

Table 1. Comparison with other works regarding the size, stop-band, thickness, and BW of array elements.

FSS	Order	f_0 (GHz)	Element Size	Ultra wide stop band	BW	Thickness
[11]	2	2.35	0.65λ	no	3%	0.01λ
[18]	2	24	0.16λ	no	19%	0.033λ
[19]	3	10	0.067λ	no	21%	0.067λ
[20]	2	8.5	0.076λ	no	10%	0.038λ
This work	2	2.45	0.05λ	yes	10%	0.033λ

Because of their relatively large size, most traditional high order band-pass FSSs are designed at the X- and Ku-bands, rather than at lower frequency, as can be observed from Table 1. The size of the proposed MFSS is very compact, and the thickness is small, which make the proposed design very suitable for low frequency and ultra-wide harmonic suppressed applications.

3. CONCLUSION

In this paper, a wide-band and ultra-wide stopband MFSS has been proposed. The thickness of the proposed structure is 0.033λ , and the element size is $0.05\lambda \times 0.05\lambda$ for the prototype, which is one of the smallest reported so far. The miniaturization and ultra-wide stopband is realized by using resonant structures on the first and third interdigital layers. The proposed MFSS is useful for low frequency and ultra-wide stopband harmonic suppressed applications. The proposed structure exhibits very good features as an FSS, such as insensitivity to the incident angle and an ultra-wide stopband. The MFSS has great potential for practical applications such as in radar and communication systems.

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