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# An Angular Stable Dual-Band Frequency Selective Surface with Closely Spaced Resonances

**Ning Liu[1], Xian-Jun Sheng[2, *], Jing-Jing Fan[2], and Dongming Guo[1]**

**Abstract**—We present an angular stable dual-band frequency selective surface (FSS) in this paper. By placing anchor-shaped elements with different structural parameters along $x$-axis alternately within hexagonal wire grid, the proposed FSS can provide two closely spaced passbands. And the resonant frequency ratios are only 1.16 and 1.19 for TE and TM polarizations, respectively. In addition, the proposed FSS has stable frequency response under oblique incidence, and resonant frequency deviation is below 0.5% within 60° incident angle. An FSS prototype is fabricated and measured for further verification, and good agreements between the simulated and measured results can be observed.

## 1. INTRODUCTION

Frequency selective surfaces (FSSs) are periodic structures and have been widely investigated for decades. Owing to the frequency filter property, FSS has been applied to construct hybrid radomes, antenna reflectors, electromagnetic shelters, spatial filters, etc. [1]. Under some special circumstances, FSSs with multiple frequency bands are desired. Especially, in multi-frequency or multi-function communication systems, FSSs with multiple frequency bands are required to increase the system's capacity and efficiency [2].

Motivated by this requirement, different approaches, such as periodic cell perturbation technique [3], fractal element [4], complementary structure [5], combined or multiresonant elements [6] and multilayer inductive and capacitive arrays [7], have been applied to design FSS with multiband characteristic. Recently, several FSS structures with closely spaced resonances have been proposed. A miniaturized dual-band FSS with closely spaced bands was presented in [8]. Branched cooked structure was adopted in [9] to design dual-band FSS with closely spaced frequency bands. A capacitive loaded FSS with closely spaced frequency response was presented in [10], and an FSS with closely spaced resonances based on meander lines was proposed in [11]. Identical resonant elements were adopted to construct FSS with closely spaced resonances in [12]. Nevertheless, these designs lack simultaneous angular stability as well as closely spaced resonances.

In this paper, an angular stable FSS with two closely spaced resonances is investigated. Compared with FSS structures mentioned above, the proposed FSS has smaller frequency ratio and better resonant frequency stability. Performance of the proposed FSS is demonstrated by both full-wave simulations and verification experiments.

## 2. FSS DESIGN AND SIMULATION RESULTS

As shown in Fig. 1, the proposed FSS is composed of anchor-shaped elements with different structural parameters arranged along $x$-axis alternately within hexagonal wire grid. And the FSS layer is mounted

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* Corresponding author: Xian-Jun Sheng (sxianjun@dlut.edu.cn).
[1] School of Mechanical Engineering, Dalian University of Technology, Dalian 116024, China. [2] School of Electrical Engineering, Dalian University of Technology, Dalian 116024, China.

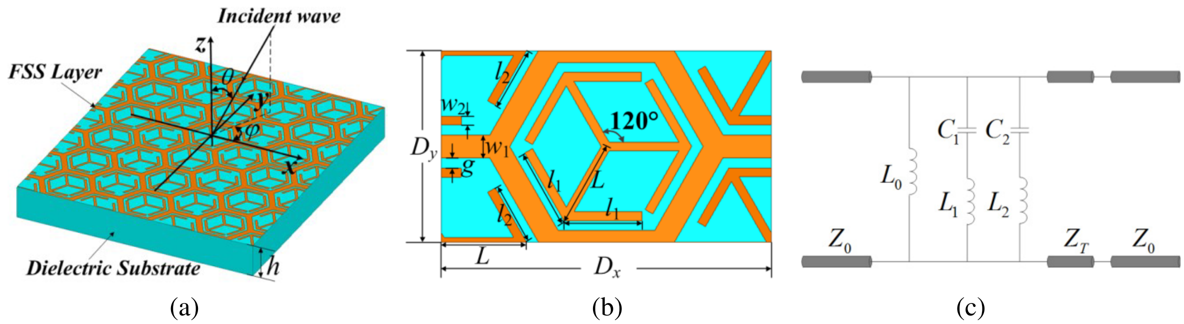



**Figure 1.** Structure of the proposed FSS structure and its equivalent circuit model. (a) Three dimensional view. (b) The unit cell. (c) Its transmission line model.

on one side of a dielectric substrate. Due to the difference in anchor-shaped elements, two resonant paths will be provided, and then two stop-bands are produced.

According to the equivalent circuit theory [13], frequency filter property of the proposed FSS can be simply analyzed via its equivalent circuit model. As shown in Fig. 1(c), the hexagonal wire grid can be modelled as an inductor $L_0$, and the anchor-shaped elements with different structural parameters can be depicted by two series $LC$ resonators ($L_1$-$C_1$ and $L_2$-$C_2$), respectively. As for the dielectric substrate, it can be modelled by a short transmission line, where $Z_0$ is the wave impendence in free space, and $Z_T$ is the wave impendence in the dielectric substrate. As indicated in Fig. 1(c), there will be two stopbands, if the two series $LC$ resonators ($L_1$-$C_1$ and $L_2$-$C_2$) resonate. Obviously, a passband will be formed between the two transmission zeroes, which are produced by the two series $LC$ resonators. Meanwhile, due to the existence of the equivalent circuit inductor $L_0$, an additional passband will be produced by the first series $LC$ resonator ($L_1$-$C_1$) and the inductor $L_0$. Based on the discussion above, the proposed FSS can produce two passbands separated by two transmission zeroes.

**Table 1.** Structural parameters of the proposed FSS element.

| Parameter | $D_x$ | $D_y$ | $w_1$ | $w_2$ |
|---|---|---|---|---|
| Value (mm) | 7.5 | 4.33 | 0.52 | 0.2 |
| Parameter | $g$ | $L$ | $l_1$ | $l_2$ |
| Value (mm) | 0.2 | 1.9 | 1.8 | 1.4 |

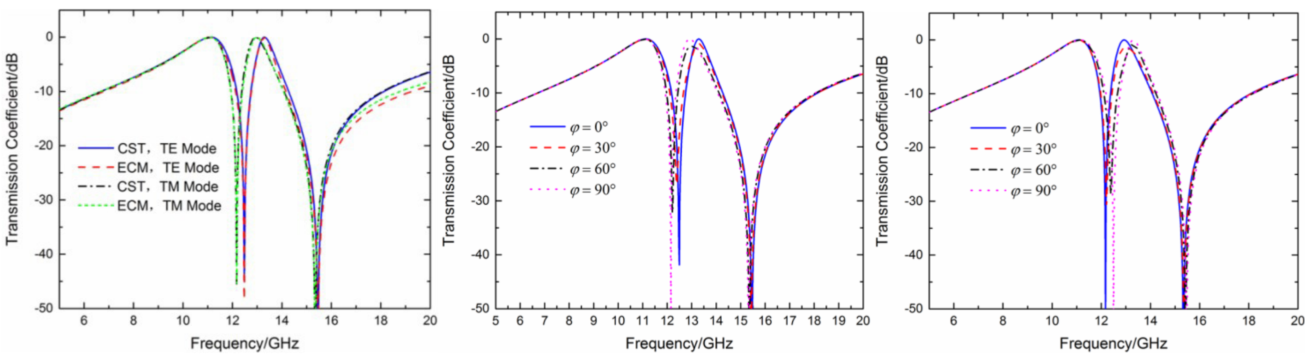
To verify the performance of the proposed FSS, simulations by commercial software CST Microwave Studio are carried out. Structural parameters of the proposed FSS layer are set and shown in Table 1. The FSS layer is mounted on an F4B-2 substrate, whose dielectric permittivity $\varepsilon_r = 2.65$, tangent loss $\tan\delta = 0.002$, and thickness $h = 1\,\text{mm}$.

Firstly, transmission coefficients of the proposed FSS at normal incidence with different polarizations are calculated and shown in Fig. 2. Based on the curve-fitting technique in [14], the frequency responses of the equivalent circuit model (ECM) obtained by ADS are also shown in Fig. 2(a) for comparison. The parameters of the lumped elements are listed in Table 2. As observed in Fig. 2, the proposed FSS can provide two close passbands separated by two transmission zeroes. For TE polarization, resonant frequencies of the two passbands are $f_{p1} = 11.13\,\text{GHz}$ and $f_{p2} = 13.29\,\text{GHz}$, respectively. And the transmission zeroes occur at $f_{z1} = 12.48\,\text{GHz}$ and $f_{z2} = 15.46\,\text{GHz}$, respectively. For TM polarization, the two passbands operate at $f_{p1} = 11.08\,\text{GHz}$ and $f_{p2} = 12.92\,\text{GHz}$, which are separated by two transmission zeroes occurring at $f_{z1} = 12.17\,\text{GHz}$ and $f_{z2} = 15.34\,\text{GHz}$. As indicated in Fig. 2(a), frequency response obtained by the equivalent circuit model agrees with the simulated one by CST Microwave Studio, and especially the resonant frequency deviation between the two methods keeps below 0.1 GHz, which demonstrates the validity and accuracy of the proposed equivalent circuit model shown in Fig. 1(c). Meanwhile, frequency responses of the FSS at normal incidence with different polarization angles are shown in Fig. 2(b) and Fig. 2(c). It can be found that frequency response of the designed FSS is sensitive to the polarization angle, and the resonant frequency deviation keeps below 2.5%.

To explain the resonant mechanism and polarization sensitivity of the proposed FSS, surface current distribution of the structure at the two transmission zeroes $f_{z1}$ and $f_{z2}$ under TE and TM polarization are shown in Fig. 3. By arranging anchor-shaped elements with different structures along $x$-axis alternately, two resonant paths will be provided, and then the two different transmission zeroes

**Table 2.** Lumped-element parameters in the equivalent circuit model.

| | | | | | |
|---|---|---|---|---|---|
| TE polarization | $L_0$ | $L_1$ | $C_1$ | $L_2$ | $C_2$ |
| | 1.15 nH | 13.56 nH | 0.012 pF | 2 nH | 0.053 pF |
| TM polarization | $L_0$ | $L_1$ | $C_1$ | $L_2$ | $C_2$ |
| | 1.2 nH | 18.98 nH | 0.009 pF | 2.15 nH | 0.05 pF |




(a) (b) (c)

**Figure 2.** Transmission coefficient of the proposed FSS at normal incidence (a) With polarization angle $\varphi = 0°$. (b) With different polarization angles for TE polarization. (c) With different polarization angle for TM polarization.

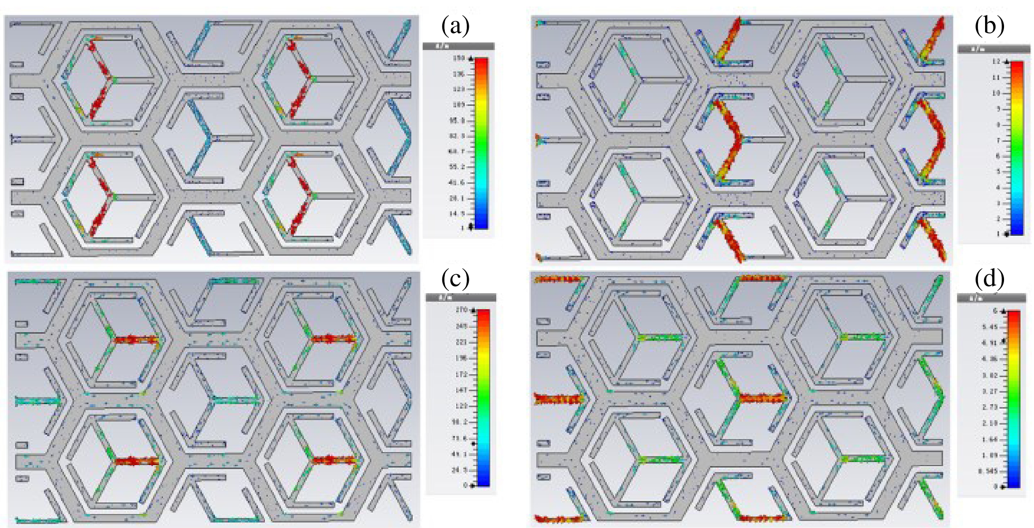
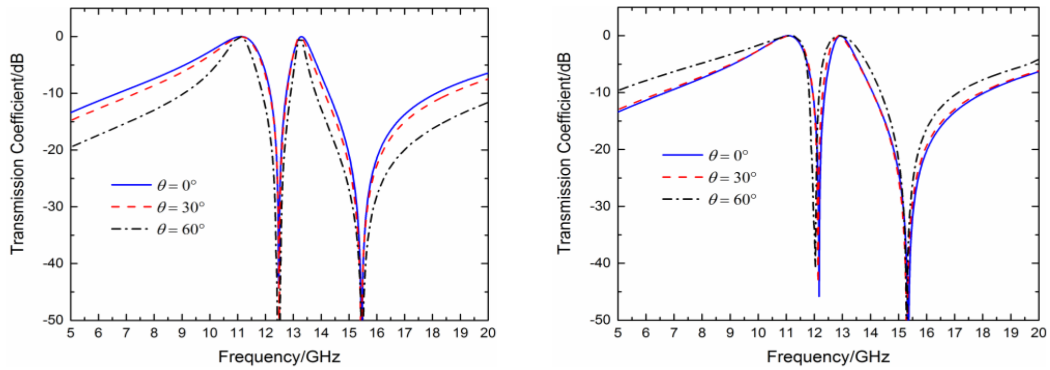



**Figure 3.** Surface current distribution of the proposed FSS for TE ((a) and (b)) and TM ((c) and (d)) polarization: (a) (c) At $f_{z1}$, (b) (d) At $f_{z2}$.




(a) (b)

**Figure 4.** Transmission coefficients of the proposed FSS structure under oblique incidence. (a) TE polarization. (b) TM polarization.

are produced. As observed, the first transmission zero is mainly produced by the anchor-shaped element with longer legs, and its equivalent circuit parameters are $L_1$ and $C_1$. Meanwhile, the equivalent circuit parameters $L_2$ and $C_2$ are mainly produced by the anchor-shaped element with shorter legs, which will form the second transmission zero operating at $f_{z2}$. As indicated in Fig. 3, due to the anchor-shaped element structure design, resonant lengths under TE and TM polarization are different. This difference in resonant length under different polarizations will lead to resonant frequency shift of the two transmission zeroes. Then, as observed in Fig. 2(b) and Fig. 2(c), different frequency responses under different polarization angles will be obtained.

Based on the discussion above, resonant frequencies of the transmission zeroes are mainly affected by the two anchor-shaped elements, and due to the difference in resonant length under different polarizations, frequency response of the designed FSS is sensitive to polarization angles. Meanwhile, due to the hexagonal wire grid structure design, an equivalent circuit inductor will be produced. Then, combined with the anchor-shaped element, the proposed FSS structure can provide two passbands, in which the first passband is mainly affected by the wire grid and the anchor-shaped element with longer legs, and the second one is mainly affected by the two anchor-shaped elements with different lengths of legs. Hence, resonant frequency and bandwidth of the passband can be changed by adjusting the corresponding structural parameters. In addition, polarization sensitivity can be compensated by decreasing the difference in resonant lengths. Based on this idea and the surface current distribution, difference in resonant lengths under TE and TM polarizations can be compensated by adopting the modified anchor-shaped element, in which lengths of the three legs are different. By properly designing lengths of the three legs, same resonant lengths under TE and TM polarizations will be formed. Then, lower polarization sensitivity will be obtained.

Subsequently, transmission coefficients of the proposed FSS at oblique incidence with different polarizations are simulated and shown in Fig. 4. It can be observed that resonant frequency of the two passbands maintains well at oblique incidence. For TE polarization, when the incident angle reaches 60°, resonant frequency deviations of the two passbands are only 0.34% and 0.28%, respectively. As for TM polarization, resonant frequency deviations are only 0.48% and 0.18%.

Finally, to verify the performance of the proposed FSS, comparisons with similar FSS structures in previous works are carried out. It can be observed from Table 3 that compared with other similar FSS structures, the proposed FSS has smaller resonant frequency ratio and better angular stability. And resonant frequency ratios of the proposed FSS are as low as 1.16 and 1.19 for TE and TM polarizations, respectively.

## 3. EXPERIMENTAL VERIFICATION

As shown in Fig. 5, an FSS prototype consisting of $40 \times 70$ elements is fabricated. Hence, the overall size is about $300\,\mathrm{mm} \times 300\,\mathrm{mm}$. Transmission coefficients of the fabricated FSS prototype are measured in a

**Table 3.** Comparisons with similar FSS structure.

| | Frequency band ratio | Resonant frequency stability |
|---|---|---|
| FSS structure in [8] | TE and TM: 1.4 | Maximum shift of 1% from 0° to 60° |
| FSS structure in [9] | TE and TM: 1.39 | Stable response upto 60° |
| FSS structure in [10] | TE and TM: 1.4 | Maximum shift of 0.7% from 0° to 60° |
| FSS structure in [11] | TE and TM: 1.29 | Maximum shift of 0.9% from 0° to 75° |
| FSS structure proposed | TE :1.19<br>TM:1.16 | Maximum shift of 0.5% from 0° to 60° |

microwave anechoic chamber with the free-space measurement system composed of two horn antennas connected to a network analyzer (Agilent N5230A). In the experiment, transmission coefficients are measured firstly without the FSS prototype, and then the measured results are adopted to modify the measured transmission coefficients with the FSS prototype. To ensure that the incident wave is plane wave, the transmitting antenna is placed about 3 m away from the fabricated FSS prototype, and the distance between the receiving antenna and FSS prototype is about 0.5 m.

The measured transmission coefficients of the fabricated FSS under different incident angles, together with the simulated ones, are shown in Fig. 6. It can be observed that the measured results agree with the simulated ones very well. And the frequency filter property maintains well under oblique

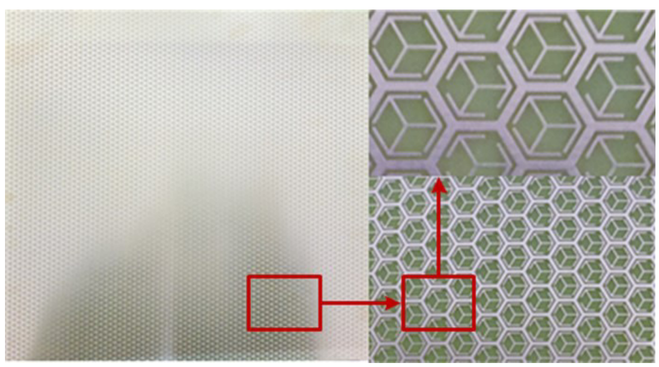


**Figure 5.** Photograph of the fabricated miniaturized FSS.

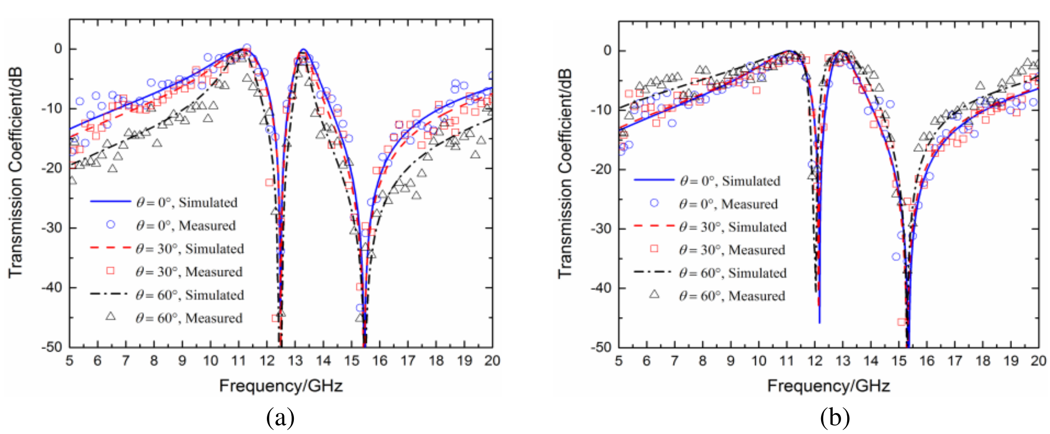



**Figure 6.** Comparisons between simulated and measured results. (a) TE polarization. (b) TM polarization.

incidence, which demonstrates the validity of the proposed FSS. Note that there are unexpected ripples in the measured transmission coefficient curves. The differences are mainly caused by the errors with measuring systems, especially the edge diffraction of the fabricated FSS prototype.

## 4. CONCLUSION

In this paper, an angular stable FSS with two closely spaced passbands are proposed. Resonant frequency ratios are only 1.16 and 1.19 for TE and TM polarizations, respectively. In addition, resonant frequency deviation is below 0.5% at oblique incidence within 60° incident angle. Consequently, compared with other FSS designs, the proposed one is a balanced design considering the angular stability as well as closely spaced resonances simultaneously. Finally, the proposed FSS is fabricated and measured, showing satisfactory agreements with the simulation results.

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## REFERENCES

1. Munk, B. A., *Frequency Selective Surfaces: Theory and Design*, Wiley, New York, 2000.
2. Yan, M., et al., "A tri-band, highly selective, bandpass FSS using cascaded multilayer loop arrays," *IEEE Trans. Antennas Propag.*, Vol. 64, No. 5, 2046–2049, 2016.
3. Hill, R. A. and B. A. Munk, "The effect of perturbating a frequency selective surface and its relation to the design of a dual-band surface," *IEEE Trans. Antennas Propag.*, Vol. 44, No. 3, 368–374, 1996.
4. Werner, D. H. and D. Lee, "Design of dual-polarised multiband frequency selective surfaces using fractal elements," *Electron. Lett.*, Vol. 36, No. 6, 487–488, 2000.
5. Hu, X.-D., et al., "A miniaturized dual-band frequency selective surface (FSS) with closed loop and its complementary pattern," *IEEE Antennas Wireless Propag. Lett.*, Vol. 8, 1374–1377, 2009.
6. Wu, T. K. and S. W. Lee, "Multiband frequency selective surface with multi-ring patch elements," *IEEE Trans. Antennas Propag.*, Vol. 42, No. 11, 1484–1490, Nov. 1994.
7. Gao, M., S. M. A. M. H. Abadi, and N. Behdad, "A dual-band, inductively-coupled miniaturized-element frequency selective surface with higher-order bandpass response," *IEEE Trans. Antennas Propag.*, Vol. 64, No. 8, 3729–3734, 2016.
8. Chiu, C. N. and W. Y. Wang, "A dual-frequency miniaturized-element FSS with closely located resonances," *IEEE Antennas Wireless Propag. Lett.*, Vol. 12, 163–165, 2013.
9. Sivasamy, R. and M. Kanagasabai, "A novel dual-band angular independent FSS with closely spaced frequency response," *IEEE Microw. Wireless Compon. Lett.*, Vol. 25, No. 5, 298–300, 2015.
10. Xu, R., H. Zhao, Z. Zong, and W. Wu, "Dual-band capacitive loaded frequency selective surfaces with close band spacing," *IEEE Microw. Wireless Compon. Lett.*, Vol. 18, No. 12, 782–784, Dec. 2008.
11. Ghosh, S. and K. V. Srivastava, "An angularly stable dual-band fss with closely spaced resonances using miniaturized unit cell," *IEEE Microw. Wireless Compon. Lett.*, Vol. 27, No. 3, 218–220, 2017.
12. Huang, F. C., C. N. Chiu, et al., "Very closely located dual-band frequency selective surfaces via identical resonant elements," *IEEE Antennas Wireless Propag. Lett.*, Vol. 14, 414–417, 2015.
13. Costa, F., A. Monorchio, and G. Manara, "Efficient analysis of frequency selective surfaces by a simple equivalent circuit approach," *IEEE Antennas Propag. Mag.*, Vol. 54, No. 4, 35–48, Apr. 2012.
14. Wang, D. S., Y. M. Chang, W. Q. Che, and Y. L. Chow, "Miniaturized dual-band loaded frequency selective surface with narrow band spacing," *Proc. ICMMT*, Vol. 5, Shenzhen, China, May 2012.