Working Principles of A Broadband/Dual-band Frequency Selective Structure with Quasi-Elliptic Response

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***Abstract*-The working principles of a novel quasi-elliptic frequency selective structure (FSS) based on apertured cavity with six ring slots are investigated completely. Similar with the elliptic filter circuits design, cross coupling is essential in elliptic FSS. The cross-coupling and the mechanism of producing transmission zeros are discussed. Besides, from the aspects of both wave construction and equivalent circuit, the operating principles are studied in details, and further verified with simulations of power flow at resonance frequencies. With the groundwork laid, two dual-band quasi-elliptic FSS are reported utilizing the same basic unit structures. The work in this paper would be beneficial to the research of frequency selective surfaces, and is especially meaningful to the development of elliptic FSS.**

I. INTRODUCTION

Frequency Selective Surface is a constantly hot research topic in the last several decades for its remarkable application value in areas such as radar cross-section (RCS) reduction, electromagnetic compatibility (EMC), communication systems, etc [1][2]. Ben.A.Munk proposed the Periodic Moment Method (PMM) which endows structural parameters with clear physical meanings. With this method, the theory, design and application of traditional FSSs have been comprehensively studied and were systematically summarized in a classical treatise [2].

The filtering responses of FSSs are dominated by unit structures. The traditional unit structures could be arranged into four groups: center connected type such as the famous Jerusalem cross and simple straight element; loop type like circular or square loops; plate types and the combination of abovementioned structures [2]. Except for these basic types, the development of computational technology boosts the designs of complicated unit structures. Rahmat-Samii et al introduced the concept of fractal to designs of multi-band FSSs[3]. Wener,D.H and Shigesawa combined the Genetic Algorithm (GA) with FSS design and optimization, and presented some heteroclite structures[4][5].

However, the traditional FSS designs are mainly with two dimensional planar unit structures. The application of single-layered traditional FSSs is limited for the drawbacks of poor filtering responses and narrow bandwidth. With the method of cascading 2-D FSSs and thin dielectric layers, the filtering responses and bandwidth could be substantially enhanced. The combined multi-layer FSSs nevertheless follow Butterworth or Chebyshev responses whose attenuation of stopband increases slowly, leading to a wide transition band[2][6]. To cut down the interference of “useless signal”, a speedy transition from passband to stopband, namely rapid rolloff of transmission responses is preferred in applications. In contrast, Elliptic response is superior in high selectivity, rapid rolloff and high attenuation in stopband, due to the transmission zeros placed near passband [7].

To design FSSs with elliptic responses, people break through the restriction of traditional planar FSSs, and proposed the innovative concept of “three dimensional frequency selective structures” [8]. A.Abbaspour developed an array of antenna-filter-antenna modules to design elliptic FSS with high-order poles [9]. Luo et al presented a class of quasi-elliptic FSS designs by introducing cross coupling in a dual-mode FSS based on substrate integrated waveguide (SIW) [10]. Shen et al contributed a series of elliptic FSS designs employing dielectric-filled waveguides, and shielded microstrip lines [11][12].

In our previous work, a broadband quasi-elliptic FSS adopting a novel apertured cavity with six ring slots was reported [13]. In this paper, its working principles would be discussed in details, and a dual-band quasi-elliptic design would be developed with the similar unit.

II. TRANSMISSION ZERO AND CROSS-COUPLING

In filter circuit, elliptic responses are commonly designed with mature theory. Transmission zeros at finite frequencies are normally obtained by introducing cross coupling between resonators [14]. Fig.1 gives the basic concepts of cross coupling and illuminates a way to design the elliptic FSSs.

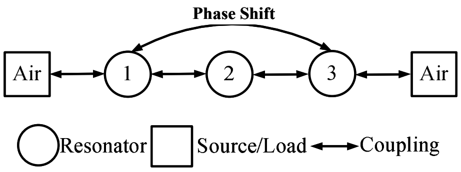

Figure 1. Cross coupling between resonators.

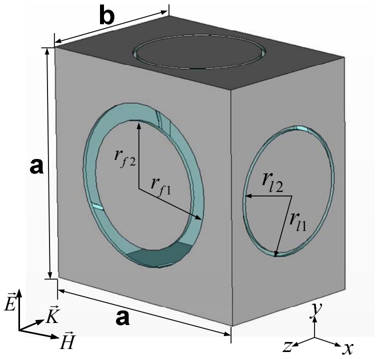

Figure 2. Unit structure and simulation configuration. a=12mm,b=8mm rf1=4.3mm, rf2=3.4mm, rl1=3.4mm, rl2=3.2mm, and thickness of the metal t=0.2mm.

With the introduction of cross-coupling, at least two parallel paths are provided for signals, and every path is with different phase shift to signal at certain frequency. Signals from different paths combine out of phase at the load or receiver, resulting to transmission zeros, while combination in phase contributes transmission poles. With the above principle, it is essential to built up parallel paths for electromagnetic waves in elliptic FSS. The unit structure in Fig.2 is a typical one. This FSS is proved to be with high selectivity, broad bandwidth, and rapid rolloff at upper band edge.

III. WORKING PRINCIPLES

The working principles of the novel structure in Fig.2 could be discussed from the view of wave propagation. The following Fig.3 is the up view inside the unit and the propagation situation is sketched. As can be seen, there are three main paths for electromagnetic waves from the front to the back of FSS: i. the incident wave passes through the front slots and directly to the free space; ii. Before transmitting to the back slots, waves are reflected by lateral slots. iii. Waves transmitting to the back slots are from the nearby units.

From the described paths, it can be found that, compared with traditional planar FSSs, the lateral rings bring another two paths and work as secondary frequency selectors. Incident waves go through the front slots, and then come to the back slots through plenty of parallel paths, thus waves to the free space are with different phase shift. Constructive superposition of these waves contributes to the passband response of the FSS. On the other hand, destructive superposition of these waves corresponds to the stopband response of the FSS.

FSS is essentially a filter in space, thus the working principles of this elliptic FSS can also be studied from the view of filter circuit. Fig.4 is the equivalent circuit of the novel FSS. As is revealed, this equivalent circuit consists of five parts, three resonators and their mutual couplings. Three resonators correspond with the three main paths in Fig.3, and their mutual influences are represented with mutual coupling circuits. For a signal at certain frequency, the resonator and coupling circuits determine its amplitude and phase together, in accordance with superposition principle in FSS.

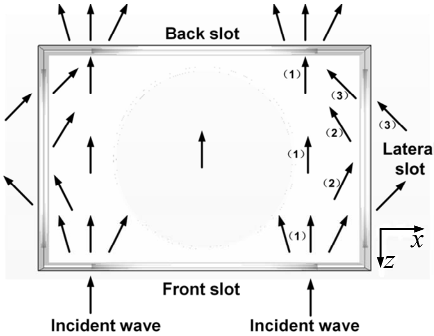

Figure 3. Wave propagation inside unit structure.

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To examine the validity of the equivalent circuit, its response is compared with the proposed FSS in Fig.5. As depicted, the responses of the equivalent circuit are almost the same with FSS, which reveals the correctness of this equivalence.

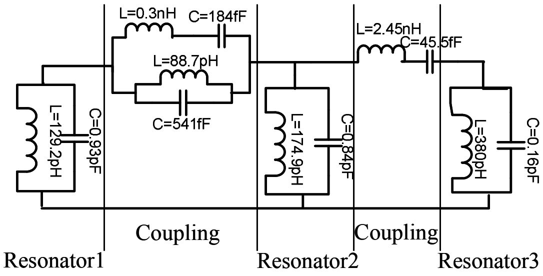


Figure 4. Equivalent circuit of FSS

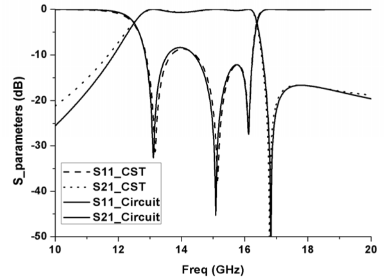


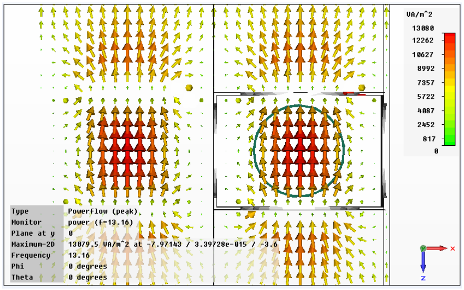
Figure 5. S-Parameters of equivalent circuit and FSS.

The filtering response of the proposed FSS is also displayed in Fig.5. In the reflection response, three resonances at 13.16GHz, 15.14 GHz and 16.12 GHz, are exhibited, giving rise to a broad 3dB passband from 12.45GHz to 16.38GHz. Besides, this FSS has a rapid rolloff near upper band edge, and its bandwidth ratio of -3dB to -0.5dB is as low as 1.13, which is much lower than the typical ratio value 3.5 of traditional FSSs. Moreover, the stopband attenuation at higher frequency is generally higher than 20dB. In conclusion, this novel FSS has a high selectivity, rapid rolloff and high attenuation in stopband.

IV. VERIFICATION

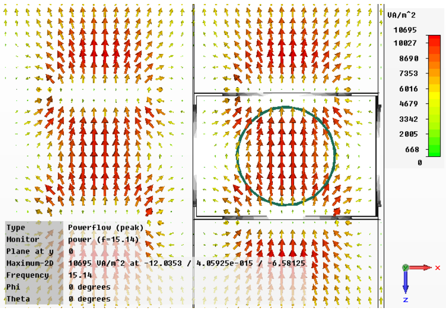
To verify the abovementioned principles, the power flow at three resonance frequencies 13.16GHz, 15.14 GHz and 16.12 GHz, is given. Fig.6 is the top view situation of power flow at 13.16GHz. As shown in the right color bar, the depth of the red color represents the intensity of power flow, namely the darker the color, the bigger the power flower. From the figure, most of the power flows from the front rings to the back slot at 13.16GHz, which corresponds to the path (1) in Fig.3. As explained in part.2, response at certain frequency is the consequence of construction of different paths, and hence some minor power is from the lateral rings resembling path (2)(3), as observed.

The power flow at 15.14GHz in Fig.7 is obviously different from Fig.6. The intensity of power flow at 15.14GHz from the path (1) and path (2) are almost equal. That is to say, waves pass through these two paths with different phase shift, and have a constructive superposition, forming the resonance at reflection response.



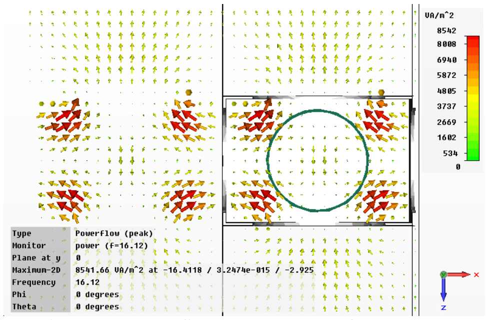
Type Powerflow (peak)
Monitor power (f=13.16)
Plane at y 0
Maximum-2D 13079.5 VA/m^2 at -7.97143 / 3.39728e-015 / -3.6
Frequency 13.16
Phi 0 degrees
Theta 0 degrees

Figure 6. Power flow at resonance of 13.16GHz.



Type Powerflow (peak)
Monitor power (f=15.14)
Plane at y 0
Maximum-2D 10695 VA/m^2 at -12.0353 / 4.05925e-015 / -6.58125
Frequency 15.14
Phi 0 degrees
Theta 0 degrees

Figure 7. Power flow at resonance of 15.14GHz.



Type Powerflow (peak)
Monitor power (f=16.12)
Plane at y 0
Maximum-2D 8541.66 VA/m^2 at -16.4118 / 3.2474e-015 / -2.925
Frequency 16.12
Phi 0 degrees
Theta 0 degrees

Figure 8. Power flow at resonance of 16.12GHz.

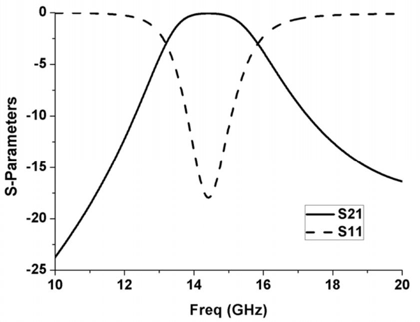


Figure 9. Responses without coupling between nearby units.

As is depicted in Fig.8, power flow at 16.12GHz is nearly all from lateral rings. However, it is hard to tell whether the wave is from the path (2) or path (3), as these two paths are very much different. Waves in path (2) have a phase shift not only from the propagation, but also have another phase shift when reflected by lateral ring slots. This additional phase shift is determined by the frequency/phase response of lateral selector.

As known, under the stimulation in Fig.2, responses of FSS could be calculated with a unit and proper boundary setting, i.e., perfect electric wall at XZ plane and perfect magnetic wall at YZ plane. According to equivalent theory, waves in path (3) could be replaced by magnetic conducting wall placed at lateral wall of the unit plus the equivalent magnetic current on it. The magnetic conducting wall and equivalent source produce another parallel path for cross-coupling.

To elucidate the function of coupling between nearby units in bringing cross-coupling and transmission zeros, the situation in which the above magnetic boundary is replaced by electric boundary is simulated. As revealed in the simulated S-parameters in Fig.9, without the coupling between nearby units, the reflection response has only one resonance. Moreover, the response is characterized with Butterworth response which is typical in multi-layered FSS.

V. DUAL-BAND QUASI-ELLIPTIC RESPONSE

Based on the working principles analyzed above, a dual-band quasi-elliptic FSS is presented by tuning the structural parameters of the unit in Fig.2. As seen in the transmission responses in Fig.10, the response in solid curve has a quasi-elliptic passband with rolloff at right edge, and an elliptic response at higher band. Two transmission zeros appear at

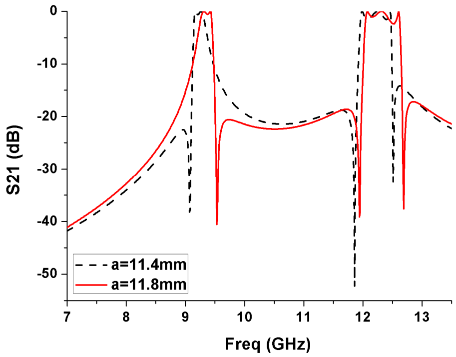


Figure 10. Dual-band quasi-elliptic responses.b=10.3mm rf1=4.78mm, rf2=2.63mm, rl1=4.47mm, rl2=0.95mm.

stopband edges between two passbands, leading to a high stopband attenuation. This unit could also be designed to achieve a quasi-elliptic passband with left-edge rapid rolloff and an elliptic passband at higher frequency band, by simply change of parameter a. These two superior responses are depicted and compared in Fig.10, and it illuminates a possible way to reach the dual-band elliptic filtering response by combining these two quasi-elliptic FSSs.

VI. CONCLUSION

This paper firstly introduced the development and limitations of traditional frequency selective surfaces, and showed examples of most recent progress in quasi-elliptic and elliptic FSS. The theory of cross-coupling and transmission zeros has been discussed and guided the analysis of working principles of the novel FSS. Connected with the unit structure, its operating principles have been fully investigated from aspect of construction of waves, as well as aspect of equivalent filter circuit. Both methods reached an agreement that the quasi-elliptic filtering responses are constructed with three resonance modes and their mutual coupling, and the parallel paths is essential for transmission zeros. The conclusions were then validated with simulations of power flow at resonance frequencies. When the coupling between nearby units is eliminated, the FSS exhibits a typical Butterworth response, which proves the necessity of parallel paths to yield transmission zeros. Moreover, two dual-band quasi-elliptic FSSs are designed with the foundation of working principles.

Further related works would be emphasized on the research of elliptic FSS and multi-band elliptic FSSs based on same basic unit structure.

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