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Review on Evolution of Frequency Selective Surfaces

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ABSTRACT: This review gives an account of the route through which Frequency Selective Surfaces have developed in form and in application over the past few decades. Different types of FSS are used based on their application as bandpass and bandstop filter. For some of these applications the geometries of the array elements can be very simple, but in cases where surfaces are curved, significantly more complicated configurations are likely to be required. Fabrication cost is an important issue.

KEYWORDS: Frequency Selective Surfaces, Periodic structures, Shielded microstrip line, Electromagnetic Wave Propagation.

I. INTRODUCTION

Frequency-selective surfaces (FSSs) have been studied over the past five decades [1, 2]. They have evolved from simple designs to the complex geometries known today. This evolution has been mainly driven by the increasingly stringent performance requirements of recent applications. Progress on frequency-selective surfaces has also been motivated by the significant improvements in analysis methods, computational power, and fabrication technology. The frequency selective surfaces (FSS) are periodic structures in either one, two dimensions (i.e. singly or doubly periodic structures) which, as the name suggests, perform a filter operation. Thus, depending on their physical construction, material and geometry, they are divided into low-pass, high-pass, band-pass and band-stop filters.

As can be seen in Figure 1 the FSS can be cascaded to form a triply-periodic structure which is commonly known as a photonic crystal. The FSS were intensively studied since the early 1960s although in 1919 Marconi patented such periodic structures[i]. From 1969 until the end of 2000, 214 papers were published containing the keyword "frequency selective surface" (INSPEC Catalogue search 12/1/2001). Early work concentrated on the use of FSS in Cassegainian sub reflectors in parabolic dish antennas. FSS are now employed in radomes (terrestrial and airborne), missiles and electromagnetic shielding applications.

The analysis of FSS started with mode matching techniques which were first applied in waveguide problems. The mode matching method led to the approximate method of equivalent circuit analysis which gave a lot of insight into the behavior of FSS since it was partly based on the transmission line principles. The modeling capability however was limited by the inability of the Mode Matching Method to model any FSS geometry and the inaccuracy the equivalent circuit method. With the advent of computers more accurate numerical techniques were developed for the analysis of FSS such as the method of moments (with entire or sub domain basis functions) the finite difference method and the finite element method.

Experiment is necessary to verify the performance of a practical FSS structures, confirm the accuracy of theoretical/numerical models and provide results for FSS structures which are not amenable to simulation. The early experiments using bolometer have now been replaced with Network Analyzers that provide the capability of obtaining not only power but amplitude and phase measurements of the scattered fields from FSS structures provided an accurate calibration is performed.

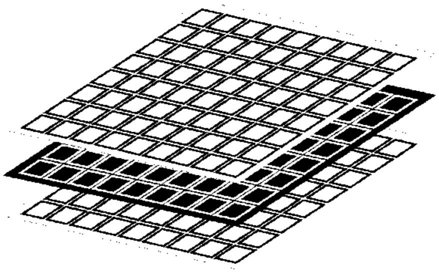
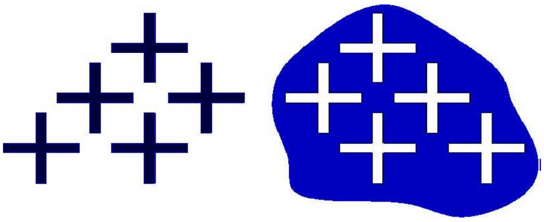


Fig. 1. Cascaded FSS.

Finally, there are the engineering and cost issues. Often FSS are limited by the precision in which they can be etched and may be required over large areas of surface. There are also difficulties, both theoretical and practical, of design and construction of FSS composites over doubly-curved surfaces. There are local cut-and-paste methods as well as global projection methods, each of which may be used as the basis of a mathematical definition as well as a means for practical construction. The former methods, e.g. [3], have more in keeping with the infinite tangent plane approximation, but lead to local discontinuities in the pattern periodicity. The latter can avoid discontinuities but give rise to significant local distortions. This is a recognized long standing problem which deserves attention at a fundamental level. Fast general purpose numerical methods which guarantee accuracy do not exist although many approximate methods have been developed which have been shown to be accurate and efficient for special classes of structure (e.g. [4]). Ray tracing approaches have also been explored, e.g. [5]. At the practical level cheap manufacture requires the processing of two dimensional flat materials using print and etches technologies.

SLOT STRUCTURES AND ELEMENT STRUCTURES:

Often an FSS or multiple FSS composite is required with a band-pass or band-stop characteristic. A single FSS with band-pass nature is topologically of slot form, where in the low frequency limit the surface is indistinguishable from a uniform perfect conductor. A single FSS with band-stop nature is topologically of dipole element form where, in the low frequency limit the surface is invisible. Perfectly conducting slot structures feature perfect electrical connections between contiguous unit cells. Conversely, dipole element structures are characterized by structures which are not connected across unit cells. The definitions apply for both single and orthogonal dual polarization use with suitable attention given to the directions of current flow across cell boundaries. For a single (thin) perfectly conducting FSS, the dipole element and slot characteristics are dual and are related by Babinet complementarily. This is only approximately true when the FSS are supported by a dielectric substrate and not true when there are multiple FSS present [1].



(a)Perfectly conducting elements (b) Slots in perfect conductor
Fig.2 Babinet complements of elements and slots

II. EQUIVALENT CIRCUIT THEORY

The use of equivalent circuit theory to represent the characteristics of FSS goes back to the origins of FSS, fifty or so years ago when full wave analysis was difficult to carry out except for the simplest structures. Quasi-static analysis may be used to represent a lossless FSS by surface impedance characterized by a simple arrangement of inductors (L) and capacitors (C). Resistors (R) are incorporated for lossy structures. Often such analysis was applied to FSS in rectangular waveguide where there is a one-to-one correspondence between the exact solution of a rectangular lattice in free space and that within the guide [6]. Accuracy is generally good up to and slightly beyond the first FSS resonance.

Equivalent circuit theory can provide useful physical insight, provide interpolation of transmission and reflection coefficients as a function of frequency and also provide methods of synthesis. This is because the response of an equivalent circuit is by definition a realizable function of frequency and there exists a well-established body of theory on the use of equivalent circuits in control theory, filter theory and circuit synthesis [7]. It may also be used in RAM design for the same reasons. However, for all but the simplest circuits, equivalent circuits are not generally unique and it may be necessary to switch between topologies depending on some external parameter if the LCR values are to remain all positive. Thus, one equivalent circuit may be good for a range of angles of incidence (with capacitors, inductors and resistors that change value with angle of incidence) but may need to be switched to another representation outside of this range. How this should best be done appears to be an area where there is little theory available and would be an interesting topic of further investigation.

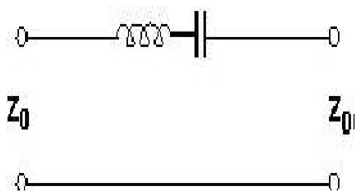


Fig.3 Simplest equivalent circuit representations of a band pass FSS in free space corresponding to a slot structure for one polarization and incidence angle.

SINGLE LAYER FREQUENCY SELECTIVE SURFACES:

Single-layer frequency-selective surfaces consist of a two dimensional periodic array of resonant shapes, as shown in Figure 4. These are classified as *open* or *closed* shapes. Open shapes, such as a dipole, resonate at a frequency when the length of the conducting wire is approximately λ /2 , where λ is the operating wavelength. On the other hand, a closed shape, such as a loop, resonates when the circumference of the shape is close to λ . These resonant frequencies are lowered by a factor of approximately $(\varepsilon_r + 1)$ 2 [1, 2, 8] when the pattern is printed on a dielectric layer, or it is slotted in a conductive layer placed right above a dielectric substrate.

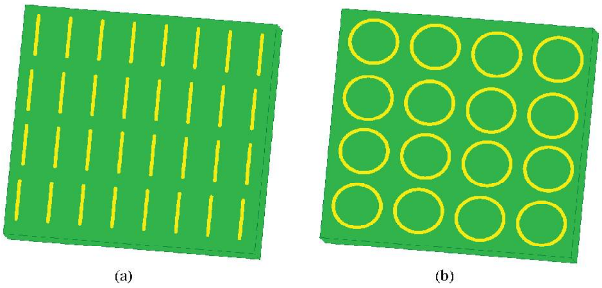


Fig 4. Typical single-layer two-dimensional frequency-selective surfaces: (a, left) printed dipoles and (b, right) printed loops.

Figure 5 shows a simple example of single-layer frequency- M selective surface, which consists of square loops printed on a thin substrate ($\varepsilon_r = 2.2$, substrate thickness = 0.1mm). A transmission zero at 10 GHz was seen in this design example. Since it strongly reflected an incident plane wave at the resonant frequency, it basically formed a band-stop spatial filter, the equivalent circuit of which was given as a series *LC* network connected across the transmission line, as shown in the insert of Figure 4. For the purpose of a detailed analysis, numerical values for *L* and *C* can be extracted, as suggested in [9]. Other open- and closed-loop shapes also lead to similar first-order filtering performance, when used in a single-layer frequency selective surface. Reference [1] compared the performance of various shapes and concluded that the square loop was one of the best elements.

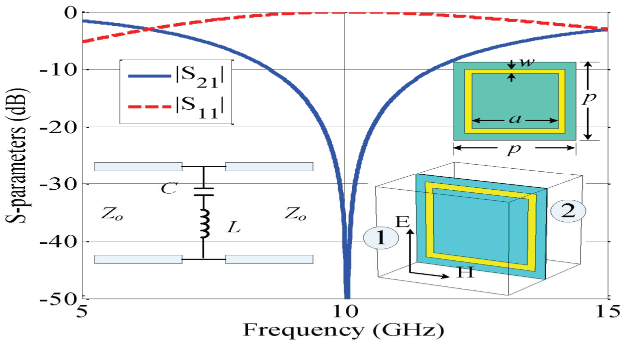


Fig 5. The *S*-parameter results and the equivalent circuit of a two-dimensional periodic array of printed loops (*w* = 0.6mm, *a* = 7.3 mm, *p* = 10 mm).

A complementary design, when these loops are etched out of a conducting surface, leads to a bandpass response, where there is minimum reflection at the resonant frequency. Figure 6 shows this example along with its equivalent circuit, which is a shunt *LC* network connected across a transmission line. The small difference in the resonant frequencies of the two complementary designs is due to the presence of a thin dielectric substrate ($\varepsilon_r = 2.2$, substrate thickness = 0.1mm). It is known that this difference of complementary structure becomes more pronounced with an increased thickness of the substrate [1].

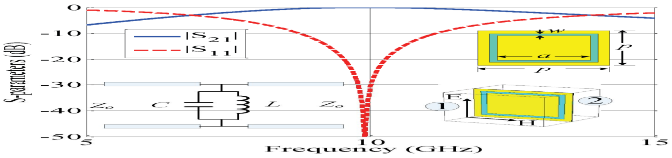


Fig 6. The *S*-parameter results and the equivalent circuit of a simple two-dimensional bandpass frequency-selective surface (*w* = 0.6mm, *a* = 7.3 mm, *p* = 10 mm).

MULTI-LAYER FREQUENCY SELECTIVE SURFACES:

A maximally-flat or Chebyshev filtering response can be obtained by cascading the conventional single-layer two dimensional frequency-selective surfaces with the insertion of thick dielectric spacers between them. The thickness of these dielectric layers is generally kept close to a quarter of a wavelength, whereby they act as impedance inverters. Equivalently, a simple cascaded combination of two-dimensional frequency selective surfaces results in a periodic arrangement of resonators and impedance inverters. Figure7 shows an example where two single layers of the frequency-selective surface in Figure 5 have been cascaded with an air space between them. We note two resonances in this case, which basically correspond to the two resonators that are separated through an impedance inverter. Adjusting the separation width, *t*, and the resonant frequencies, the position of these two resonances can be controlled to obtain a maximally flat or an equal-ripple response. As shown in the inset of Figure 7, the equivalent circuit is that of direct-coupled resonators, which are known to follow a Butterworth or Chebyshev response [10].

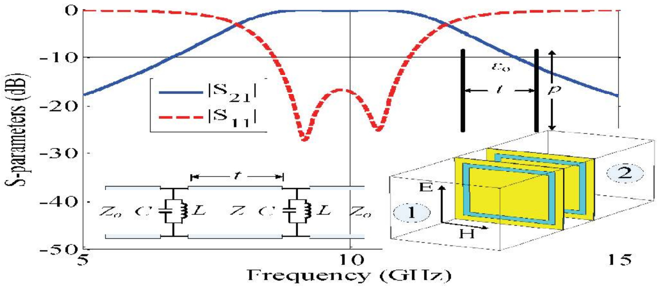


Fig 7. The *S*-parameter results and the equivalent circuit of a cascaded combination of two single-layer band pass frequency-selective surfaces of Figure 3 (*w* = 0.6mm, *a* = 7.3 mm, *p* = 10 mm, *t* = 5mm).

Most of the practical frequency-selective surfaces used in real applications actually consist of multilayer designs [1, 2]. Their analysis becomes relatively simple by treating them as a cascaded combination of *S*-parameter matrices [11]. It is not necessary to combine identical two-dimensional structures, as done in the example of Figure 7. Instead, a cascaded combination of dissimilar two-dimensional frequency-selective surfaces may lead to much improved performance in terms of sharp rejection skirts. An example is given in Figure 8, where a bandpass two-dimensional frequency-selective surface was sandwiched between two band-stop frequency-selective surfaces. It is seen that the bandpass frequency-selective surface created a transmission pole at 11 GHz. The original response of a single slotted loop was like that of Figure 4, which did not exhibit a sharp rejection profile. However, since this two-dimensional frequency-selective surface was cascaded with two band-stop frequency-selective surfaces, its response became much steeper, due to the existence of two transmission zeros. In Figure 8, these transmission zeros are seen at 5 GHz and 14.5 GHz. An equivalent circuit of this example is given in Figure 9, which shows three cascaded resonators.

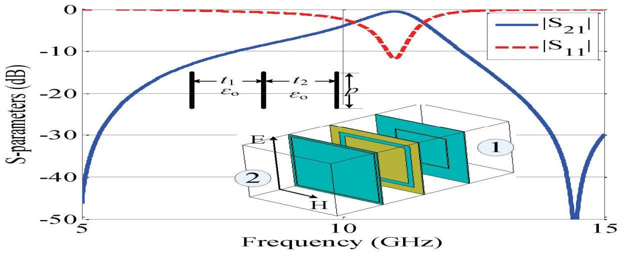


Fig 8. The *S*-parameter results of a cascaded combination of a bandpass and two band-stop frequency-selective surfaces (the variable names and geometry are consistent with those in Figures 4 and 5; $w1$ = 0.1mm, $a1$ = 9.3mm, $w2$ = 0.6mm, $a2$ = 8 mm, $w3$ = 0.1mm, $a3$ = 5.6mm, p = 10 mm, $t1$ = 4.5mm, $t2$ = 5mm).

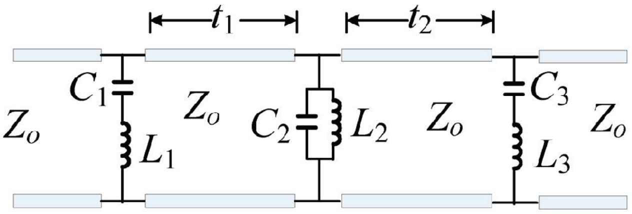


Fig 9. An equivalent circuit for the frequency-selective surface

III. THREE DIMENTIONAL FREQUENCY SELETIVE SURFACES

A three-dimensional frequency-selective structure consists of a two-dimensional periodic array of multimode cavities, as depicted in Figure 10. This multimode cavity may be a substrate integrated waveguide (SIW) structure [12,13], a microstrip line or other suitable geometries. One may obtain a desired frequency response by controlling the number of propagating modes and their couplings with air [14]. Based on that, the frequency-selective structure design procedure is similar to that of waveguide elliptical filters [15-17]. Given a center frequency and design specifications, one may first obtain a suitable coupling matrix [17]. A multimode cavity can be selected, the modes of which are known. The coupling of air to each mode, and the resonant frequencies of the modes, can be adjusted to match the synthesized coupling matrix. The procedure becomes more involved, since one needs to repeat the procedure under different angles of incidence. However, it is already known that unit cells with sub-wavelength transverse dimensions lead to an angularly stable frequency response [1, 2]. Based on that, one may synthesize a structure under the case of normal incidence only, when the transverse dimensions of the chosen multi-mode cavity are smaller than the operating wavelength. This conclusion can also be verified from the results in [9 where a very stable frequency response was noted under even a large variation of the angle of incidence. Figure 11 shows an equivalent circuit of a simple dual mode three-dimensional frequency-selective structure, like the narrowband case presented in [9]. The two resonators are represented by the *LC* lumped elements, which are coupled to air at two sides through M_{S1}, $M_{S\,2}$, and M_{L1} , M_{L2} . The incident plane wave is represented by a voltage source, E_s . This equivalent circuit is consistent with the commonly used networks for dual-mode waveguide filters [10]. Since there are four loops in the circuit, it leads to a 4 × 4 coupling matrix [10] characterizing this frequency-selective structure. As the two modes belong to the same cavity, they are orthogonal, and their mutual coupling can be neglected. Based on that, the coupling matrix of this simple case reduces to:

$$\begin{bmatrix} 0 & M_{S1} & M_{S2} & M_{SL} \\ M_{1S} & M_{11} & M_{12} & M_{1L} \\ M_{2S} & M_{21} & M_{22} & M_{2L} \\ M_{LS} & M_{L1} & M_{L2} & 0 \end{bmatrix} = \begin{bmatrix} 0 & M_{S1} & M_{S2} & 0 \\ M_{S1} & M_{11} & 0 & M_{S1} \\ M_{S2} & 0 & M_{22} & M_{S2} \\ 0 & M_{S1} & M_{S2} & 0 \end{bmatrix}.$$

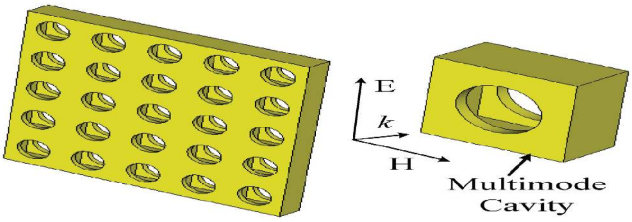


Fig 10. An illustration of a three-dimensional frequency selective surface consisting of a two-dimensional periodic array of multimode cavities.

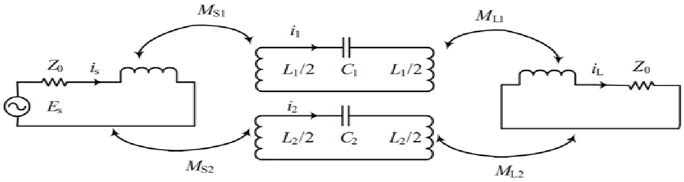


Fig 11. The equivalent circuit a dual-mode three-dimensional frequency-selective structure.

IV.CONCLUSION

An emerging new class of frequency-selective structures has been reviewed, which consists of a two-dimensional periodic array of three-dimensional unit cells. It offers an arbitrarily pseudo-elliptical performance by exciting a suitable number of propagating modes, and controlling their coupling with air. FSS have a long pedigree and are used for a number of applications including antenna reflectors, radomes, radar absorbent materials and composite metamaterials. There are many well established design tools and the theory is well developed although there remain a significant number of problem areas of practical and theoretical interest, such as the design and construction of FSS on doubly curved surfaces and the effect of non-periodicity. There are exciting new fronts developing for their use within metamaterials where the use of three dimensional structures, tight coupling between FSS layers and/or the flow of electric currents perpendicular to surfaces using conducting vias is key to controlling the effective permittivity and permeability tensors of the materials.

It is hoped that this review provides a useful perspective. It has been discussed that the use of microstrip-line resonators can actually lead to many more desirable features, which may not be easily realizable in traditional frequency-selective surfaces. It should be mentioned that a three-dimensional frequency selective structure is relatively difficult to fabricate, compared with traditional cascaded combinations of two-dimensional surfaces and dielectric layers. However, this difficulty in fabrication can be compensated for by its superior performance.

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