Miniaturized-Element Frequency Selective Surfaces

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Abstract

This article presents an overview of the progress made in the design of surface topology, fabrication, and applications of a new class of spatial filters known as miniaturized-element frequency selective surfaces (FSS’s) in recent years at the University of Michigan. The research in designing the new class was initiated with the demand for FSS’s with overall small dimensions for low frequency applications and reducing the dependence of the frequency selective properties of the FSS surfaces on the incidence angle of the incoming plane wave. Traditional FSS’s are usually fabricated from resonant elements, whose dimensions are usually comparable with half a wavelength, arranged in a periodic fashion. Proper operation of such surfaces can be achieved only when a large number of periods are included in a finite surface since the overall response is affected by the interaction among all Bragg modes of the periodic structure. This is also the reason for angular dependence of the frequency response of most old FSS’s. In the new class, these effects can be circumvented through sub-wavelength localization of the filtering phenomena. To achieve such objectives, the use of spatial lumped elements, printed on a substrate surface, are considered which allows for a decrease in the unit cell dimensions to be on the order of a tenth of the wavelength or smaller. It will be shown that by cascading surfaces containing these spatial lumped elements, band-pass, stop-band, or any other filter responses of a desired order can be generated. It is also discussed that the interaction of such surfaces and incoming wave is predominantly in TEM mode, resulting in suppression of all higher-order Bragg modes and elimination of the harmonic responses. As a demonstration, designs featuring high-order, band-pass characteristics with a single and dual transmission zero using only a single substrate are presented. Moreover, producing a frequency response that is tunable or even metamorphic, which can be transformed from a band-pass response to stop-band, by incorporating varactors onto the structure of the new FSS’s is investigated. Next, multi-band characteristics of the new class in a multi-layer arrangement are presented. Investigations are currently under the way to develop a practical implementation of electronically tunable FSS’s using the elements of the FSS itself as bias circuitry of tuning components mounted on the surface.

1. Introduction

A typical frequency selective surface (FSS) is constructed from a 2D-periodic planar structure consisting of one or more metallic patterns, each backed by a dielectric substrate with a frequency response that is entirely determined by the geometry of the structure in one period called a unit cell. These surfaces have been the subject of research over the past years for a variety of radar and communications applications [1]-[4]. Recently, however, attentions are more concerned on adapting such surfaces for relatively small antennas with electrically small aperture and possibly with a capability of agile multi-band operation. A salient feature of such FSS screens ought to be insensitivity of their response with respect to the angle of incidence. The design of a new class of FSS structures, the miniaturized-elements FSS’s, were first considered in [5] to mainly deal with such issues. This article presents an overview of recent advances in the design of miniaturized-elements FSS surfaces as well as future trends.

The initial concept of the miniaturized-element FSS can be traced back to the two-sided circuit board in [5]. It consists of a periodic array of metallic patches backed by a wire mesh having the same periodicity much shorter than the wavelength. The array of patches constitutes a capacitive surface and the wire mesh a coupled inductive surface (Fig. 1), which together act as a resonant structure in the path of an incident plane wave. Due to a high external coupling coefficient, such a primitive single-pole design has shown to have a poor selectivity and a high insertion loss. To remedy this major shortcoming, two cascaded surfaces with proper coupling were devised to obtain a band-pass response with much better performance [5]. However, large electrical separation remained an issue as regards to fabrication, mounting, and again producing angle of incidence dependence to some extent.

In the next stage, the design of the miniaturized-element FSS was modified and improved to overcome the performance and the assembly issue [6]. The improved design, loop-wire FSS (see Fig. 2), produces a high-Q, high-order, band-pass characteristic using just a single-substrate screen. The periodicity, moreover, is reduced by at least a factor of two, making the unit cell dimensions as small as $\lambda_0/12$. These improvements are achieved noting that: 1) the loop surface behaves as notch filter capable of producing a transmission zero, 2) both electric and magnetic mutual coupling are established between the two surfaces using a very thin substrate. A lumped capacitor can be inserted in the gap between the loops to avoid issues related to fabrication of capacitance values beyond what can be achieved by air gaps. The loop-wire design exhibits not only a better frequency selectivity, compared to the first generation, but also a much better insensitivity to incidence angle. The detailed performance characteristics of this FSS and the related physical behavior of the components are discussed in detail in [6]. Based on the analysis presented in [6], an accurate circuit model for the FSS that can fully describe the frequency response was developed (Fig. 3). The measured performance of the loop-wire FSS at X-band is provided in Fig. 4 for different incidence angles. The fabricated circuit board is shown in Fig. 5.

In another effort, the tunability of this class of frequency selective surfaces was studied. The basic idea was to interconnect loops with lumped varactors. These varactors are placed in series and can be biased with a very high voltage DC power supply. However, this is undesirable due to single point failure issue. Designing a parallel architecture biasing network for varactors for these FSS’s may not be possible. Based on the simulation results, the structure shows a great potential for wide tuning range with a negligible loss of performance. The simulation results for sweeping the pass-band of the loop-wire FSS over the frequency is shown in Fig. 6.

The next generation of the miniaturized-element FSS was
designed with the intention of improving the frequency selectivity without increasing the fabrication complexity. For this design a two-sided substrate having a periodic array of loops either side was devised. For this design, the loop array on one face was translated in both x and y directions by half a period. This allows establishment of proper electric magnetic mutual coupling between the two surfaces. The loops on each surface have the ability to create a transmission zero. Placing two such transmission zeros on either side of the pass-band frequency produces much improved frequency selectivity and out-of-band rejection. A typical frequency response of the loop-loop FSS at S-band is provided in Fig. 7 where the transmission zeros are clearly observable.

Similar to loop-wire structure, the loop-loop surface can also be tuned by placement of varactors in the gaps between the loops. Comparing to Fig. 7, Figure 8 shows the center frequency tuning by modifying the value of lumped capacitance between loops in simulation. The loop-loop FSS shows an additional interesting behavior if the varactors on the both sides are tuned a specific fashion. As the varactors are changed the transmission zero frequency on one side or both sides can be tuned. In a way, a metamorphic frequency response can be achieved by tuning the varactors. This metamorphic behavior refers to two totally different modes of operations: band-stop and band-pass. The band-pass behavior of the response can also be reconfigured for single- or multi-band, without introducing frequency harmonics of the response. For example Fig. 9 shows transition to a band-stop response. In addition to two completely different modes of operation, the center frequency as well as the bandwidth of the response can be tuned independently. Frequency tunability with a constant bandwidth over 3GHz-3.5GHz has been accomplished. A bandwidth tuning from 3% BW to 10% BW is also demonstrated.

Next, the multi-pole characteristics of the miniaturized-element FSS’s were considered. Being the standard approach of creating a multi-pole filter, cascading previously designed single-band surfaces used to construct multi-pole structures. Simply, a few FSS layers were stacked along with dielectric spacers between the layers. These designs were then further improved, in terms of selectivity and number of metal faces, by designing a single-sided loop-wire FSS which was used as building-blocks of stacked, multi-pole FSS structures. The performance of the multi-pole surfaces was tested through experiment. The results are shown in Fig. 10.

2. Miniaturized-Element FSS’s: Future Work

A feature of interest in design of FSS’s is the ability to electronically tune the frequency response of the surface. Two major approaches include either changing the structure geometry using RF-MEMS technology [7]-[8], or manipulating the FSS layers’ reactive characteristics by incorporating tuning elements into the layers’ design [9]-[10]. As mentioned above, the loop-wire and the loop-loop FSS’s can be used for this purpose, but are difficult to bias in a parallel configuration. This is due to the required biasing network which perturbs the desired frequency response of the FSS. Currently, a different FSS screen, wire-wire FSS, is being investigated and fabricated. In this design, the bias network is a part of the structure itself, but varactors can be biased in series configuration. The tuning circuitry, as a result, will not
perturb the FSS response. This FSS consists of two wire layers, like those used previously, along with vertical via holes through the substrate that are used to complete the bias circuitry. The tuning of this structure is achieved by varactors that interconnect the wire layers through the vias. The tunability of this FSS has been tested by full-wave simulations (Fig. 11). Further optimizations of the new design, however, are still required.

### 3. Conclusion

A number of important variations of the miniaturized-element frequency selective surfaces have been presented in this article. A salient feature of these surfaces is their localized properties, meaning that each element of the FSS can produce the desired frequency selective behavior with minimal dependence on the neighboring elements. This independence is mainly due to the interaction of the surface and the incoming plane wave being predominantly in TEM mode. As a result, higher order Bragg modes are suppressed, and harmonic responses are eliminated. The new FSS’s, therefore, are expected to be suitable for moderate size antennas’ applications at low frequencies.

### 4. References