Thin and Low-Profile Miniaturized-Element Frequency Selective Surfaces with Higher-Order Band-Pass Responses

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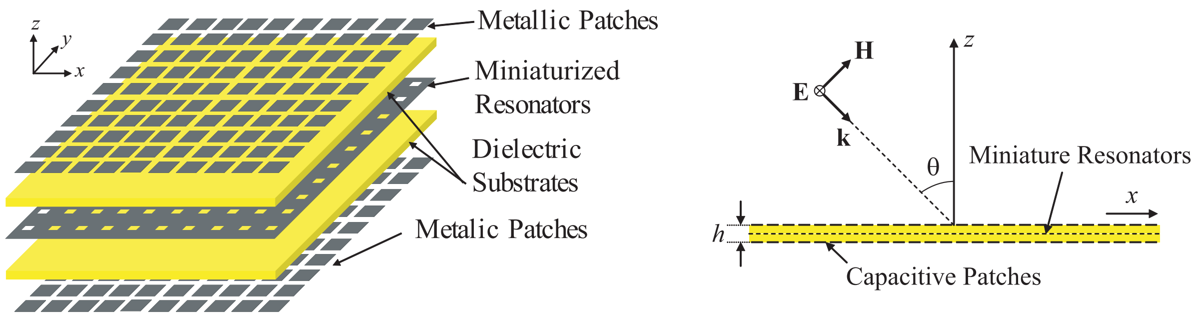
Abstract

A new class of low-profile frequency selective surfaces (FSS) with an overall thickness of λ/30 and a third-order band-pass frequency response is presented in this paper. Unlike traditional FSS design techniques, the proposed structure utilizes a combination of non-resonant and resonant constituting elements and has miniaturized unit cell dimensions and periodicities. The combination of its ultra-small thickness and miniaturized unit cell dimensions ensures that the frequency response of the structure does not significantly vary as a function of the incidence angle. Operations principles of the structure as well as measurement and simulations results are presented and discusses in this paper.

1. Introduction

Frequency selective surfaces (FSSs) have been the subject of intensive investigation for their widespread applications as spatial microwave and optical filters for more than four decades [1]-[4]. Several excellent books have also been devoted to the theoretical analysis and design of these structures [5-6]. Traditional FSSs are usually constructed from periodically arranged metallic patches of arbitrary geometries or their complimentary geometries having aperture elements similar to patches within a metallic screen [5]. These surfaces exhibit total reflection or transmission in the neighborhood of the element resonances for the patches and apertures respectively. The most important step in the design process of a desired FSS is the proper choice of constituting elements for the array and appropriate determination of the structure's periodicity. The element type and geometry, the substrate parameters, the presence or absence of superstrates, and inter-element spacing are the most important parameters that will determine the overall frequency response of the structure, such as its bandwidth, transfer function, and the dependence of its frequency response on the incidence angle and polarization of the incident EM wave. One common feature of the traditional FSS design techniques, widely used nowadays, is that they use resonant type constituting unit cells such as a resonant dipole, slot, circular or rectangular rings, etc. [5]. In such structures, the size of the resonant elements and the inter-element spacing are generally comparable to one-third to half a wavelength at the desired frequency of operation. However, in practical applications, FSSs are not infinite in extent and have finite dimensions. Therefore, to observe the desired frequency response, the finite surface must include a large number of the constituting elements and be illuminated by a planar phase front. For some applications, such as low-frequency antenna radomes or frequency selective EMI shielding, FSSs of relatively small electrical dimensions that are less sensitive to incidence angle and can operate for non-planar phase fronts are highly desirable. Furthermore, FSSs designed using traditional techniques and composed of resonant elements demonstrate a first-order band-pass or band-stop response. In situations were a high out of band rejection or sharp transmission response is required, multiple FSS panels are cascaded with a quarter-wavelength spacing between each panel. Therefore, FSSs with higher-order band-pass responses are usually thick and bulky. This reduces their attractiveness for applications where conformal FSSs are required.

In this paper, a new technique for designing frequency selective surface is presented which provides a novel method for designing low-profile band-pass spatial filters with third-order filter responses. The basic structure proposed in this paper is composed of two arrays of sub-wavelength capacitive patches separated from a periodic array of miniaturized slot antennas using two very thin dielectric substrates. The resulting structure has three layers covered with metal patterns and two very thin dielectric substrates. It is shown that the proposed structure acts as an



(a) (b)

Fig. 1. Topology of low-profile, third-order band-pass FSS. (a) 3D perspective view (b) Side view

FSS with a third-order band-pass filter. As a result of its low profile and sub-wavelength periodicity, the frequency response of the proposed structure is less sensitive to the angle of incidence EM wave compared to other third-order band-pass FSSs designed using traditional techniques. Moreover, the overall thickness of this third-order structure is between 15 to 30 times smaller than the thickness of the third-order FSSs designed using traditional techniques.

2. Principles of Operation and FSS Design

The topology of the proposed third-order band-pass FSS structure is shown in Fig. 1. Fig. 1(a) shows a three-dimensional topology of different layers of this FSS. The structure is composed of three different metal layers separated from one anther by two very thin dielectric substrates. The top and bottom metal layers consist of identical two-dimensional periodic arrangements of sub-wavelength capacitive patches. The center metal layer consists of a two-dimensional periodic arrangement of miniaturized slot antennas etched into a ground plane. The capacitive patch layers are identical and the dielectric substrates are also identical resulting in a symmetric structure with respect to the plane containing the miniaturized slot antennas. Fig. 1(b) shows the side view of the FSS. The overall thickness of the FSS, h, is twice the thickness of the dielectric substrates used to fabricate the structure on. At X-band frequencies this thickness can be made as small as 200 μm to as large as a few millimeters. This corresponds to an overall electrical thickness of $0.006\lambda_0$ to $0.1\ \lambda_0$. Fig. 2 shows the top view of different layers of the unit cell of the proposed FSS. Each unit cell has maximum physical dimensions of D_x and D_y in the x and y directions, respectively, which are the same as the period of the structure in the x and y directions. On the left hand side of Fig. 2, the top view of a single capacitive patch is shown. Assuming that the structure has the same period in x and y directions, each capacitive patch will be in the form of a square metallic patch with side length of D-s, where s is the separation between the two adjacent capacitive patches. Since the structure has sub-wavelength periods and dimensions, i.e. D_x, $D_y \ll \lambda_0$, the capacitive patches are non-resonant and their 2-D periodic arrangement simply presents a capacitive wave impedance to an incident EM wave. The right hand side of Fig. 2 shows the top view of the miniaturized slot antenna used in the unit cell of the FSS. Unlike the capacitive patches, this element is a resonant element. However, it is designed to occupy an overall area significantly smaller than regular dipole or slot antennas. As seen in Fig. 2, the aperture of each slot antenna occupies an area of $D_{ap} \times D_{ap}$, where D_{ap} is only a fraction of the unit cell size ($D_{ap} < D_x$, D_y). The topology of the miniaturized slot antenna used in the unit cell of the proposed structure was first introduced in [7] and details of its operation along with its behavior as a miniaturized slot antenna are extensively discussed in this reference. The miniaturized slot antenna shown in Fig. 2 is single polarized and, in the arrangement depicted in this figure, radiates an electric field polarized in the y direction. Therefore, the frequency response of the proposed FSS utilizing this embodiment of the miniaturized slot antenna is polarization sensitive. If polarization discrimination is not required, a dual-polarized version of the miniaturized slot antenna shown in Fig. 2 may be used.

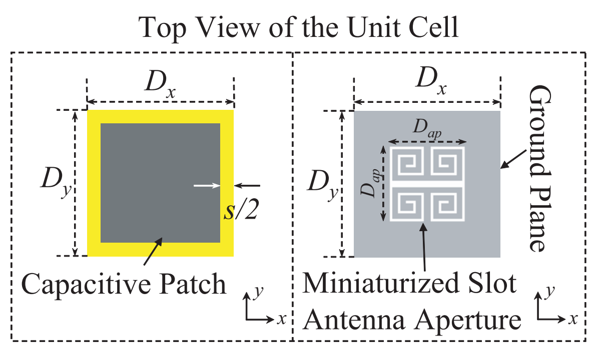


Fig. 2. Top view of the unit cell of the third-order band-pass FSS discussed in Section 2.

To understand the principles of operation of the FSS, it would helpful to consider its equivalent circuit. A simple equivalent circuit of the proposed FSS, for a vertically polarized TEM plane wave, is shown in Fig. 3. The circuit is composed of a parallel LC resonator (L_1 and C_1) with a parasitic series inductor (L_2), separated from two parallel capacitors (C_2) with two short sections of transmission lines with characteristic impedance of Z_1 and length of ℓ. The parallel resonator represents the miniaturized slot antenna. The series inductor, L_2 represents the parasitic inductance associated with the electric current flowing in the ground plane of the slot antenna. The dielectric substrates supporting the structure are modeled with two short pieces of transmission lines where the length of each line, ℓ, is equal to the thickness of the substrate, h, and the characteristic impedance of each line is $Z_1 = Z_0/\sqrt{\varepsilon_r}$, where Z_0=377Ω is the free space impedance and ε_r is the dielectric constant of the substrates used. Free space on both sides of the FSS is modeled with two semi-infinite transmission lines with characteristic impedances of Z_0. The equivalent circuit model of the FSS shown in Fig. 3 is basically a third-order band-pass microwave filter composed of two slow-wave capacitively loaded transmission line resonators separated from a parallel LC resonator with two simple impedance inverters.

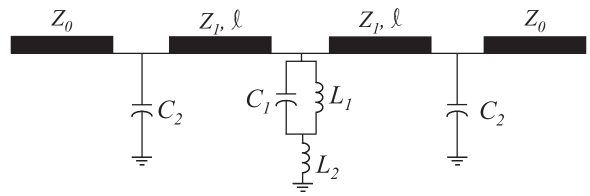


Fig. 3. The equivalent circuit model of the third-order band-pass FSS presented in Section 2.

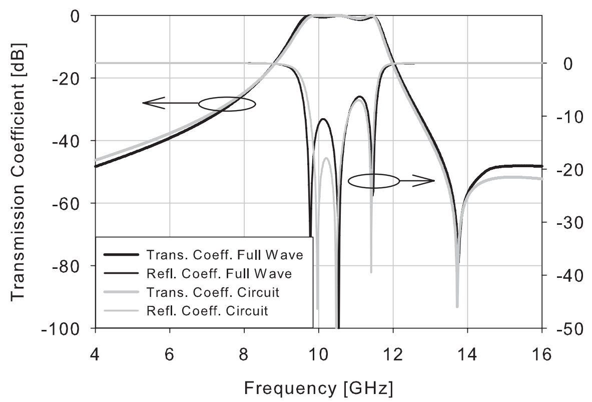


Fig. 4. Transmission and reflection coefficients of a third-order band-pass FSS of the type shown in Fig. 1. The full-wave simulation results as well as the results obtained from equivalent circuit are shown.

Table 1 shows the equivalent circuit parameter values as well as the physical and geometrical parameters of a prototype FSS similar to the one shown in Figs. 1 and 2. Fig. 4 shows the FSS frequency response as obtained from full-wave EM simulations in CST Microwave Studio as well as those predicted by the equivalent circuit model presented in Fig. 3. It is observed that the equivalent circuit model accurately predicts the FSS frequency response. The frequency response of the proposed FSS is also calculated for non-normal angles of incidence and the results indicate that the frequency response of the FSS is stable for incidence angles ranging from θ=0° to θ=60°. For lack of space, the results for oblique angles of incidence are not included here and will be presented in the symposium. This structure demonstrates a rather stable frequency response as a function of angle of incidence without the aid of any dielectric superstrates that are commonly used to stabilize the frequency response of FSSs for oblique angles of incidence [5].

Table 1. Physical and electrical parameters of a prototype FSS. All dimensions are in mm, capacitance values are in pF and inductance values are in pH.

Parameter	h	ε_r	C_1	L_1	C_2
Value	0.5	3.78	22.7	9.6	0.36
Parameter	L_2	D_x	D_y	s	D_{ap}
Value	15.2	5.5	5.5	0.06	1.46

3. Measurement Results and Experimental Verification

The performance of the proposed FSS is experimentally demonstrated using simple waveguide based measurements. Using this approach, a section of an X-band third-order band-pass FSS, especially designed for integration with a rectangular waveguide, is designed and integrated with a WR-90 rectangular waveguide. Fig. 5 shows a section of the proposed third-order band-pass FSS, which is designed to be integrated with a WR-90 waveguide. The section has dimensions of *0.9″* × *0.4″*, which are equal to the inside dimensions of a WR-90 waveguide. The structure shown in Fig. 5 is composed of a miniaturized slot resonator sandwiched between two capacitive irises. The two capacitive irises are fabricated, each on one side of two separate *0.5* mm thick RO4003 dielectric substrate from Rogers Corp. The substrate has a dielectric constant of ε_r=3.4, loss tangent of $\tan\delta$ = 0.0022 and copper cladding thickness of 18 μm. On the other side of one of these substrates, the miniaturized slot

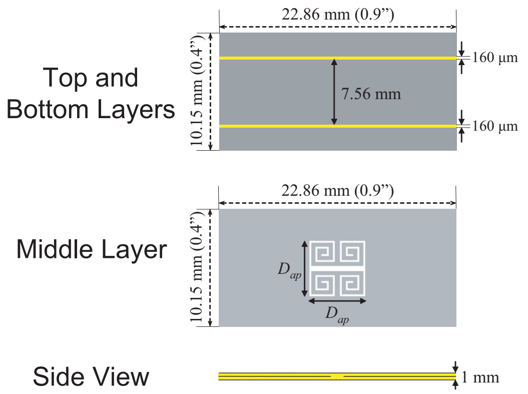


Fig. 5. Topology of the test sample of a third-order band-pass FSS designed for integration with a WR-90 waveguide.

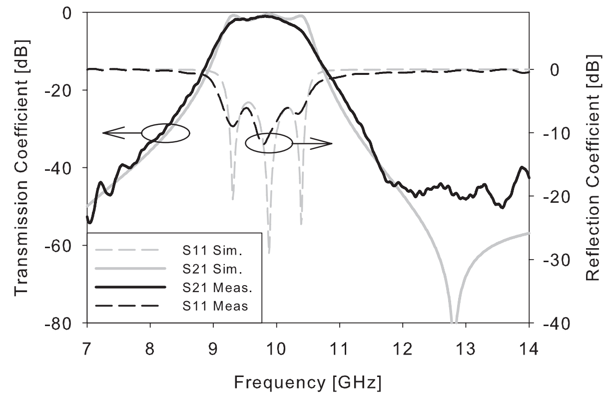


Fig. 6. Measured and simulated reflection and transmission coefficients of the test sample of the third-order FSS.

resonator is fabricated and the other side of the second substrate is completely etched to remove all the existing metal. These substrates are then connected together to form the third-order FSS shown in Fig. 5. As observed from the side view of the structure shown in Fig. 5, the entire FSS panel is only 1 mm thick. The slot resonator has aperture dimensions of $D_{ap} \times D_{ap}$ = 1.4 mm × 1.4 mm. The waveguide FSS test sample is then placed inside a WR-90 waveguide section and its frequency response is measured. Fig. 6 shows the measured frequency response of the FSS along with the full-wave EM simulation results obtained in Ansoft's High Frequency Structure Simulator (HFSS). As can be seen from this figure, a relatively good agreement between the measured and simulated results is observed. The main differences observed between the simulated and measured results can be attributed to working out of the recommended frequency range for the WR-90 waveguide sections as well as the coax to waveguide transitions used in the measurement. Nevertheless, a relatively good agreement is observed between the simulated and measured transmission and reflection coefficient within the X-band. This confirms the fact that the proposed structure acts as a third-order band-pass FSS and the validity of the design procedure presented in this paper. At its center frequency of operation, the fabricated FSS demonstrates a measured insertion loss of about 1 dB, which is mainly attributed to the Ohmic and the dielectric losses of the structure.

4. Conclusion

A new technique for designing low-profile frequency selective surfaces with third-order band-pass responses was presented in this paper. The proposed technique allows for designing third-order band-pass FSSs with an extremely small overall profile. It was demonstrated that using this technique, third-order FSSs with an overall thickness of $0.033\lambda_0$ or smaller can easily be designed. The validity of the proposed concept was experimentally demonstrated by fabricating an FSS test sample and measuring its frequency response using simple measurements in a rectangular WR-90 waveguide.

5. References

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