A Low Profile Second-Order Frequency Selective Surface with Miniaturized Elements

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Abstract

In this paper, a new approach for designing low profile second-order band-pass frequency selective surface (FSS) is presented. The proposed design utilizes non-resonant sub-wavelength constituting unit cells with unit cell dimensions and periodicities in the order of 0.15λ. The FSSs presented in this paper have an overall thickness of $\lambda_0/30$, which is considerably smaller than thickness of second-order FSSs designed using traditional techniques. Two band-pass FSS prototypes operating at X-band are designed, fabricated, and tested. A free space measurement setup is used to thoroughly characterize the frequency responses of these prototypes for both TE and TM polarizations and various angles of incidence. The frequency responses of these structures show a relatively low sensitivity to the angle of incidence. The principles of operation, design procedure, and measurement results are presented in this paper.

1. Introduction

Frequency selective surfaces have been the subject of intensive investigation by many researchers. These structures are used in a variety of different applications ranging from microwave systems and antennas to radar and satellite communications. A Frequency Selective Surface (FSS) is a periodic structure usually composed of an assembly of identical elements arranged in a one or two-dimensional lattice. In their simplest form, these elements can be in the form of metallic patches with a specific pattern or the complementary of the metal patches having apertures similar to the metallic patches etched in a ground plane. Traditional FSS design techniques often use periodic arrays of resonant elements to achieve band-pass or band-stop behavior. Using these techniques, a periodic array of slot elements can be designed to demonstrate a first order band-pass response. In this case, the unit cell dimensions and the periodicity of the structure are in the order of λ/2 to λ/3. To achieve higher-order band-pass responses, multiple FSS panels must be cascaded with a quarter wavelength spacing between each panel. This cascading not only increases the thickness of the higher-order FSS, but also increases the sensitivity of its response to the angle of incidence. To stabilize the frequency response of such FSSs, often thick layers of dielectric superstrates are employed, which will further increase the thickness of the structure. This prohibits the utilization of these structures in applications where conformal FSSs are required to cover structures with moderate to small radii of curvature.

Many techniques for designing frequency selective surfaces have also been reported. In [1], the FSS response is obtained by changing the coupling aperture dimensions between the two arrays of patch antennas. In [2], the design is based on antenna-filter-antenna concept. In all these techniques, the unit cell is still in the range of λ/2. Recently, a new class of FSS with miniaturized elements is presented by [3]. Unlike other techniques, the constituting elements of the unit cell FSS are sub-wavelength non-resonant structures. However, a higher order response of this class of FSS is achieved by cascading multiple layers with quarter wavelength spacing between the layers. This results in a thick and bulky structure and does increase the sensitivity of the frequency response of these structures to the angle of incidence. In this paper, a new technique for designing low-profile frequency selective surfaces, with second-order band-pass responses, is presented. In this technique, the constituting elements of the FSS are sub-wavelength non-resonant structures that are combined to create a second-order band-pass filter. Both the unit cell dimensions and the periodicity of the structure are considerably smaller than those observed in traditional FSSs. Furthermore, the overall thickness of the second-order FSS presented in this paper is only *λ/30*, which is also considerably smaller than the overall thickness of traditional second-order FSSs. The combination of miniaturized unit cell dimensions and the low profile of the structure results in a frequency response with a low sensitivity to the angle of incidence of the EM wave.

2. Design Procedure

Figure 1 shows the three-dimensional view and the topology of different layers of the FSS of this study. The structure is composed of three different metal layers separated from one another by two very thin dielectric substrates. The top and bottom metal layers consist of two-dimensional periodic arrangements of sub-wavelength capacitive

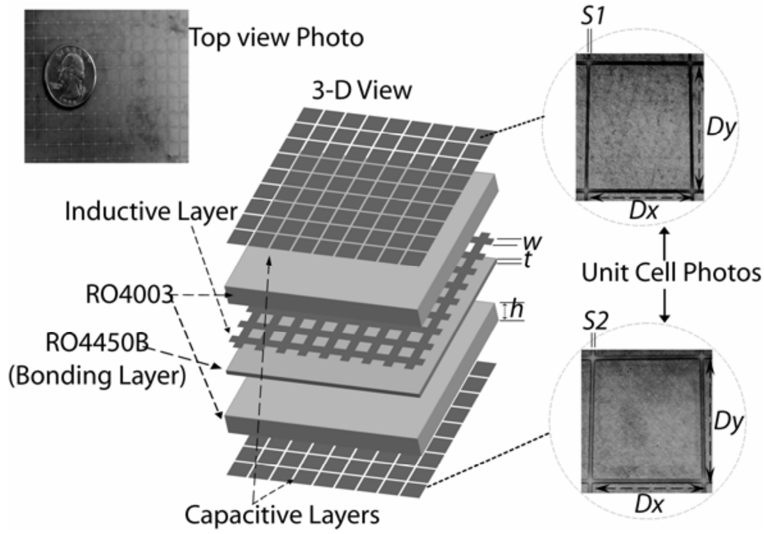

Figure 1: Topology and photograph of the fabricated FSS prototype utilizing regular patch capacitors. A bonding layer (RO4450B) is used to bond the two substrate layers and its effect must be considered.

patches. The center metal layer consists of a two-dimensional periodic arrangement of metallic strips. A bonding film is used in order to bond the two substrates. The design parameters of the unit cell are listed in Table 1. Figure 1 also 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 also the same as the period of the structure in the x and y directions. Each capacitive patch in the capacitive layer is 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. The 2-D periodic arrangement of these patches simply presents capacitive wave impedance to an incident electromagnetic wave. For a substrate with a specific dielectric constant, the capacitance value increases as the unit cell dimension, D, is increased or the spacing, s, is decreased. Figure 1 also shows the top view of the inductive strips used in the middle layer of the unit cell of the FSS. Assuming that the structure has the same period in x and y directions, the inductive layer will be in the form of two metallic strips perpendicular to each other with a length of D_x=D_y=D, and width of w. To better understand the principles of operation of this structure, it is helpful to consider its simple equivalent circuit shown in Figure 2. The patches in the first and third metallic layers are modeled with parallel capacitors (C_1 and C_3), while the wire grid layer is modeled with parallel inductor (L_2). The substrates separating these metal layers are represented by two short pieces of transmission lines with characteristic impedances of $Z_1 = Z_0 \big/ \sqrt{\varepsilon_r}$ and lengths of ℓ_1, where ε_r *is* the dielectric constant of the substrate and Z_0 = 377Ω is the free space impedance. Free space on both sides of the FSS is represented by semi-infinite transmission lines with characteristic impedance of Z_0. This circuit model basically represents a second order band-pass microwave filter. The filter is composed of two slow-wave capacitively loaded transmission line resonators separated from each other by an inductive impedance inverter. The impedance inverter is a simple inductive inverter utilizing transmission lines with negative electrical length [4]. The circuit model shown in Figure 2 is a reduced model of the actual filter, where the negative lengths of the transmission lines used in the inductive impedance inverter are absorbed in the positive lengths of the capacitively loaded transmission lines. The center frequency and bandwidth of the filter are determined by changing the operating frequency of the resonators and the coupling coefficient between them.

The FSS presented in this paper can be designed using a simple and systematic approach. The design procedure starts with the equivalent circuit model shown in Figure 2. The characteristic impedances of transmission lines and their lengths are determined by the supporting substrates used. The inductor and capacitor values are then optimized to achieve the desired frequency response. The optimization process can be performed using simple circuit simulation software such as Advanced Design System (ADS) from Agilent Corp. Then, the frequency response of the FSS is simulated using full wave numerical electromagnetic (EM) simulation. The simulations are carried out using High Frequency Structure Simulator (HFSS) from Ansoft Corp. The transmission and reflection coefficients of this structure are then simulated and the frequency response of the infinitely large structure is obtained. By choosing a sub-wavelength initial value for the period of the structure, D, the initial values of s (spacing between adjacent patches) and w (wire width) can be approximated [5]. In doing this, the desired inductance (L_2) and capacitance (C_1 and C_3) values obtained from circuit simulations are used to obtain the w and s values. The frequency response, obtained from full-

Parameter	D	W	s_1
Value	5.8mm	2.5mm	0.15mm
Parameter	s_2	h	t
Value	0.18mm	0.5mm	0.091mm

Table 1. Physical parameters of the patch FSS prototype shown in Figure 1

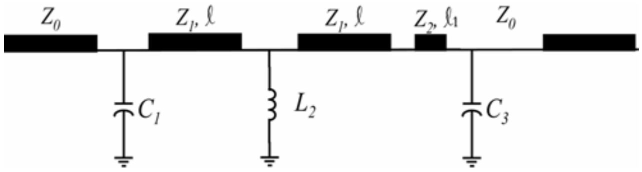

Figure 2: A simple equivalent circuit model for the low-profile FSS shown in Figure 1

wave EM simulation, is then compared to that obtained from the equivalent circuit model. The geometrical parameters of the FSS are then modified to match the frequency response obtained using full-wave simulations to the desired frequency response. This procedure is performed iteratively until the desired frequency response is achieved. The above mentioned technique is followed to design an X-band band-pass FSS. The FSS is designed using two layers of RO4003 substrate (from Rogers Corp.) with dielectric constant of ε_r=3.38, loss tangent of $tan(\delta)$=0.0027, and substrate thickness of 0.5*mm*. This FSS has a unit cell dimension of 5.8mm, which is <λ/5, where λ is the free-space wavelength at 10 GHz. The bandwidth of the FSS can be controlled by changing the coupling coefficient between the two resonators. Decreasing the coupling value decreases the FSS BW and vise versa. The coupling decreases when the inductor value, L_2, is decreased. However, this requires increasing the capacitance value, C_1 and C_3, to maintain the frequency of operation. To reduce the sensitivity of the response of the FSS to the angle of incidence, the unit cell size of the FSS can further be miniaturized. This is accomplished by reducing the unit cell dimensions while maintaining the effective capacitance and inductance values. If the unit cell size, D, is decreased, the capacitance value can be maintained by decreasing the spaces between the patches, s, or increasing the effective side length of the capacitor. Decreasing the spacing is feasible in theory but is limited by fabrication techniques used. Therefore, achieving very small s values is very difficult and requires special fabrication conditions. Thus, to increase the capacitance within the same occupied area, interdigital capacitors can be used.

3. Experimental Verification and Experimental Results

The principles of operation of the proposed FSS are experimentally verified by fabricating two prototypes of the FSSs similar to the structure presented in Section 2 and measuring their frequency responses using a free space measurement setup. The fabrication is performed by first patterning the capacitive and inductive layers on two sides of a 0.5*mm* RO4003 substrate. The other capacitive layer is patterned on one side of another substrate while etching away the copper cladding on the other side. The two substrates are then thermally compressed together with a bonding film (RO4450B) with the thickness of 0.091*mm* in between them. The physical dimensions of the fabricated prototypes are 20.3*cm*×25.4*cm*, which correspond to electrical dimensions of 7λ×8λ. This ensures that the FSSs are excited with a uniform plane wave in free space measurements. The diffraction from the edges of the FSS panel is another problem that affects the measurement accuracy. To minimize this effect, a fixture is made out of copper with very large dimensions 120*cm*×90*cm* with an opening of 20.3*cm* × 25.4*cm* in the center to accommodate the FSS panel. The FSS measurement system consists of two standard horn antennas operating at the X-band with the fixture placed in between. The line of sight between the two antennas passes through the center of the fixture and the antennas are located about 90*cm* apart from each side of the fixture to ensure the formation of a uniform plane wave impinging upon the FSS surface.

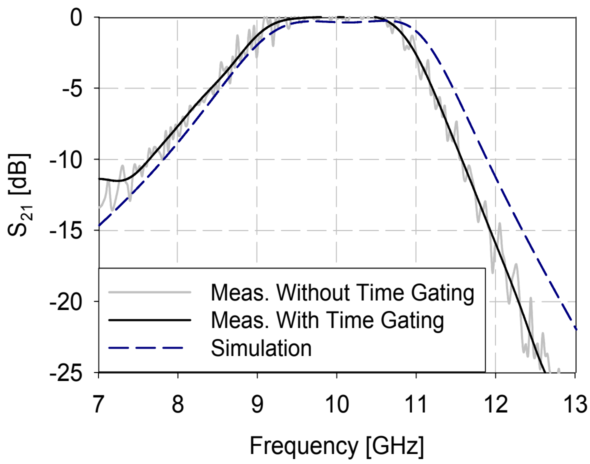

Figure 3: Comparison between simulated and measured (with/without time gating) responses of patch FSS prototype.

The measurement of the fabricated FSS is performed in free space and the result is presented in Figure 3. As observed from this figure, the frequency responses obtained using this technique has ripples over the measured frequency range. These ripples are caused by the multiple reflections between the two antennas. To remove these ripples, the normalized response is transformed to the time domain. The FSS response is then gated in the time domain and only the main transmission is retained. Then, the gated data is transformed back to the frequency domain and the ripples are removed to obtain the clear frequency response shown in Figure 3. The Figure also includes the full-wave EM simulation result obtained in Ansoft HFSS. As can be seen from this figure, a good agreement between the measured and simulated results is observed within the X-band. At the center frequency of operation, the fabricated FSSs demonstrate a measured insertion loss of about 0.3 dB, which is mainly attributed to the Ohmic and the dielectric losses of the structure. The sensitivity of the response of the structure to the angle of incidence is also examined for both fabricated FSS prototypes. Figure 4(a) shows the measured frequency response of the patch FSS prototype for the TE polarization and various angles of incidence. As expected, as the angle of incidence of the TE mode increases, the ripple level increases and bandwidth decreases. The structure demonstrates a relatively consistent response for the TE polarization for incidence angles in the range of $0^o < \theta < 45^o$. The discrepancy between the measurement and simulation results is attributed to working out of the operating bands of the standard X-band horn antennas, the coax to waveguide transition, and numerical errors in simulations. The frequency response of the patch FSS prototypes for the TM mode and various angles of incidence is shown in Figure 4(b). The measured frequency response is found to be more sensitive to the variations of the angle of incidence for the TM polarization. Nevertheless, the structure demonstrates a relatively consistent response for the TM polarization for incidence angles in the range of $0^o < \theta < 30^o$.

4. Conclusion

A new technique for designing frequency selective surfaces with second-order band-pass responses was presented in this paper. The proposed technique allows for designing second-order band-pass FSSs with an extremely small overall profile. It was demonstrated that using this technique, second-order FSSs with an overall thickness of $0.03\lambda_{,}$ can easily be designed. The principles of operation of the proposed FSS and the design procedure were presented in this paper. The experimental verification of the proposed concept was then introduced by fabricating two FSS panels and measuring its frequency response and their sensitivity to the angle of incidence. The interdigital FSS (smaller period) shows less sensitivity to various angles of incidence than the patch FSS. The full measurements will be presented in the conference.

5. References

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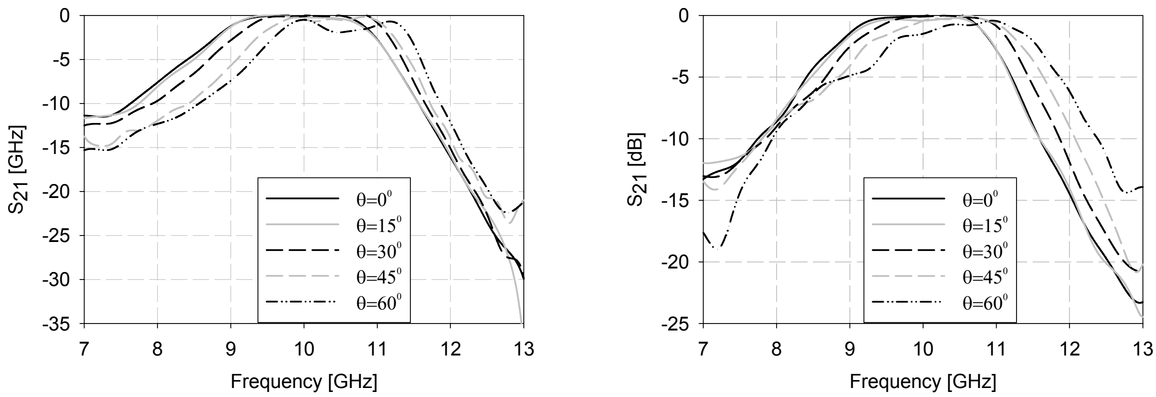

(a) TE mode (b) TM mode

Figure 4: Measured frequency responses of the fabricated patch FSS prototype for both polarizations and various angles of incidence.