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Parametric performance analysis of the square loop frequency selective surface

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Abstract. In this paper the effects of parameters of a square loop frequency selective surface to the resonance frequency is studied. Side length of the square loop, width of the conducting patch, thickness and the substrate are varied and their effects on resonance frequency evaluated via a Finite Integration Technique (FIT) based simulator. The absorption and reflected characteristics and the transmission and shielding characteristics of the proposed structure are evaluated in terms of the parametric changes.

Keywords: Frequency selective surface, Square loop FSS, Resonance frequency,

1 INTRODUCTION

Development of the technology for the application areas such as broadband communication, radar systems, and antenna technology, has reached a level of maturity so that a demand on filtering the plane waves at any incident angle is raised recently. For this purpose, frequency selective surfaces (FSSs) are constructed for mainly filtering the plane waves as periodic structures [1]. These angular depended behavioral structures can have band-pass or band-stop ability according to the various situations based on the combinations of different geometry, material properties and incident angle. In the literature, bandwidth and frequency stability are determined as the most important features of FSSs [2]. Besides the numerous advantages, FSSs are preferable since they increase the directivity, gain and purity of the received signal in antennas [2]. In addition to the effects in antenna technology FSS are popular in radome design and radar cross section (RCS) reduction since they provide frequency filtering. Usage of the FSS in periodic band–gap structures and double negative materials make the FSS more attractive. To touch upon the structure, the construction of FSSs can be explained primarily. Mainly FSSs are classified into two according to the type of their construction as planar and non-planar. The planar FSSs can either be printed on substrates or consist of loaded elements. As an advantage, they can be designed as single or multi-layer structures. Furthermore, there are not any limitations about their shape so that they can be designed in any desired shape. The freedom in choosing the material type, shape and orientation make these structures increasingly popular and various FSSs presented in the literature [1]-[8].

Although there are several studies that present FSS in different geometries, mostly designs depend on trial-error methods. In this study, one of the most popular FSS that is designed in a structure of a square loop conducting patch with a dielectric substrate on the bottom of it, is evaluated in terms of its parameters. Side length of the square loop, width of the conducting patch, thickness and the permittivity of the substrate are determined as the parameters since they affect the S-parameters of the FSS in both size and material manner. Thus, there will be information about characteristic of the S-parameters and structure properties besides trial error method.

This paper presents the effects of these parameters which are analyzed via the FIT based CAD solver. For this purpose, variations of the parameters such as the bandwidth, resonance frequency and gain are analyzed. While analyzing the structures, the conducting patch is determined as copper with a thickness of 35 μm. It is also considered that the incident plane wave is a perfect uniform plane wave with 90^{o} with respect to the plate.

2 GEOMETRY OF THE PROPOSED FREQUENCY SELECTIVE SURFACE

The proposed unit cell geometry consists of a square loop conducting patch on a dielectric layer. The top and side view of the unit cell is presented in Figure 1.

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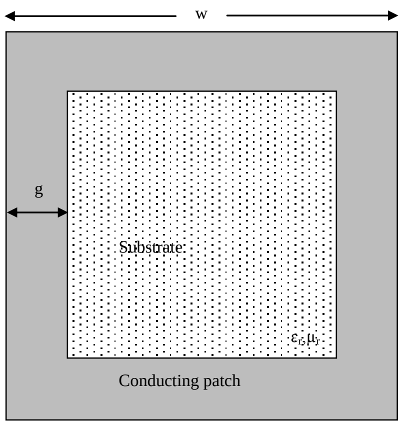
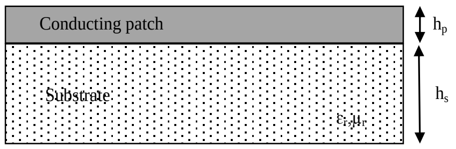


a)



b)

Figure 1: a) Top view of the unit cell FSS structure, b) Side view of the unit cell FSS structure

The side length of the square is denoted as *w*, and the width of the conducting patch is denoted as *g* as seen in Figure 1. The structure has a substrate thickness of h_s and the following material electrical properties: relative permittivity (ε_r) and relative permeability (μ_r). The thickness of the conducting patch is represented as h_p with a value of 35 µm, which is referred in many studies in the literature as the achievable thickness with even ordinary printed circuit board technologies. For that purpose, the default thickness of the conducting patch is assumed to have a thickness of 35 µm and the effects of physical parameters to the *S*-parameters are analyzed.

3 ANALYSIS OF S-PARAMETERS WITH THE VARIATION OF THE PARAMETERS OF UNIT CELL STRUCTURE

As mentioned in previous sections, FSS periodic structures may have ability to pass or stop the plane waves. They may filter the plane waves or let them pass. In order to illustrate the situation, Figure 2 may be considered. The plane waves cannot pass across the structure given in Figure 2 a) while the waves can in Figure 2 b) [9]. The figure simply demonstrates the incident and reflected components of the plane wave. In other words, Figure 2 illustrates a structure reflecting the incident wave; so that for the frequency that this reflection occurs, the S_{11} parameter will be under -10dB. However in the illustration 2b) S_{11} is equal to 0 dB; therefore, no reflection occurs.

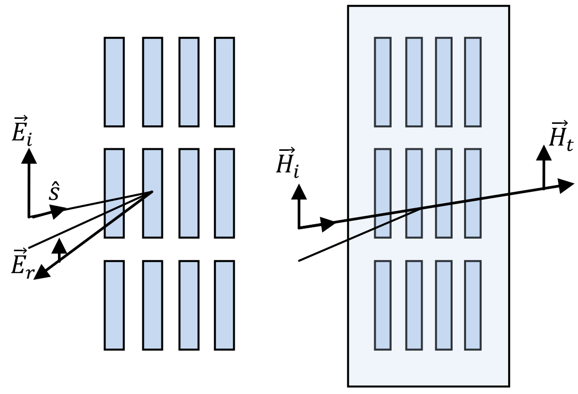


Figure 2 : a) Band-stop, b) Band-pass FSS structures

It is stated that the material properties may be the most crucial parameter in designing both band-pass and band-stop FSSs. It is also underlined that mostly the narrow band or broad band property are affected from the material properties [9]. Although it seems that material property has the biggest impact in determining the FSSs S-parameters, every single parameter related to the FSS has a significant effect in most cases. Especially the arrangement of the elements plays an important role, and they are even grouped according to the arrangements. In this study, we considered square loop FSSs, which belong to the group of loop types denoted as Group 2 in [9]. It is a well known fact that almost every single change in physical environment changes the scattering properties of a unit cell FSS. In a general point of view these changes can be related with physical size and material properties.

In this study, a square loop FSS considered and it is evaluated in terms of size and material properties. The effects of these parameters are analyzed via FIT based solver. The results are presented in the following sections.

3.1 *Reflection and absorption characteristics*

Researchers conduct series of studies related with FSSs and search for their reflection and absorption characteristics to apply in to a proper application area. In a nut shell, the S_{11} parameter shows the reflection and absorption characteristic of the material. The erstwhile studies showed that the FSS structure reflects the power if the return loss is under -10dB. Namely, the S_{11} parameter shows that the FSS reflects the considered frequency if it has a value of under -10dB; and it absorbs if it has a value almost equal to 0dB. The proposed structure is evaluated in terms of reflection and absorption characteristics. Their resonance frequencies are presented which are physically determining their reflection characteristics with respect to the change in their physical properties.

3.1.1 Effect of side length (w) to the S_{11}-parameter

In order to evaluate the side length effect on the resonance frequency of a FSS structure, 3 different side lengths are considered that are 10mm, 13 mm, and 15mm, respectively. As mentioned before the thickness of the conducting patch is determined as 35 µm and the thickness of the substrate is 1mm for all three conditions. The resonance frequencies of a FSS structure made up of silicon with a permittivity value of 11.9 are analyzed via FIT based simulation program and the results are presented in Table 1.

Table 1: Resonance frequency of a square loop FSS structure for ε_r=11.9, h_s=1mm, h_p=35µm

g	Resonance Frequency (GHz)		
	w=10mm	*w*=13mm	*w*=15mm
0.5	7.71	6.37	5.76
1	8.76	7.25	6.46
1.5	9.77	7.86	6.95
2	10.83	8.43	7.39
2.5	12.68	9.06	7.87
3	13.65	9.79	8.35

For silicon composed FSS, the resonance frequency is decreased with the increase in side length. For a conducting patch width of 0.5mm the resonance frequency is decreased from 7.71GHz to 5.76GHz when the side length is increased to 15mm from 10mm. The conducting patch width is increased up to 3mm with a step size of 0.5mm and in all steps the larger side length cause lower resonance frequency.

Without changing the physical dimensions, the substrate is changed to mica and FR4 with a permittivity of 7.9 for the former and 4.4 for the latter. The results of the mica composed FSS is demonstrated with Table 2.

Table 2: Resonance frequency of a square loop FSS structure for ε_r=7.9, h_s=1mm, h_p=35µm

g	Resonance Frequency (GHz)		
	w=10mm	*w*=13mm	*w*=15mm
0.5	9.55	7.97	7.15
1	10.89	8.91	7.98
1.5	12.08	9.61	8.50
2	1328	10.23	8.96
2.5	14.6	10.91	9.45
3	16.20	11.73	9.97

Similar characteristics is observed with the mica composed FSS as in the silicon one. The resonance frequency of the structure is increased with the increment in conducting patch width and larger side length cause again lower frequencies. The simulation procedure is repeated with FR4 substrate and related results are shown in Table 3.

Table 3: Resonance frequency of a square loop FSS structure ε_r=4.4, h_s=1mm, h_p=35µm

g	Resonance Frequency (GHz)		
	w=10mm	*w*=13mm	*w*=15mm
0.5	13.50	11.20	10.10
1	15.08	12.25	10.90
1.5	16.23	12.88	11.41
2	17.39	13.44	11.81
2.5	18.90	14.06	12.21
3	20.96	14.86	12.73

The increment in side length *w* causes a decrement in resonance frequency of the structure in Table 1, and Table 2 and 3 are in agreement with these characteristics.

3.1.2 Effect of patch width (g) to S_{11}-parameter

The patch width *g* has also an effect on the resonance frequency of the FSS. Although it can be seen from the Tables above, in order to make it clearer, the variation of the patch width is shown in Figure 3.

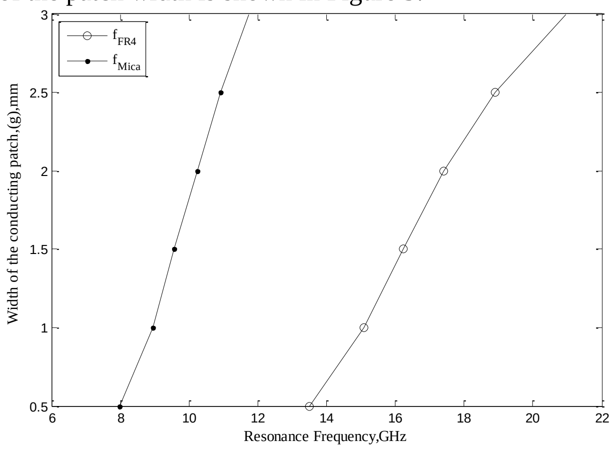


Figure 3: The effect of the conducting patch width to the resonance frequency of square loop FSS structure h_s=1mm, h_p=35µm, *w*=10mm for both FR4 and Mica

As seen in figure above the resonance frequency of FSS with FR4 is 13.5GHz for a conducting width of 0.5mm, and 20.96 GHz for a width of 3mm. The same characteristics are observed for mica and for both in other substrates. It is observed that a wider conducting patch width causes a larger resonance frequency. Silicon composed FSS is also evaluated for the same geometry and it is in an agreement with these characteristics, as well.

3.1.3 Effect of Thickness of the substrate (h_s) to S_{11}-parameter

The substrate thickness has again a significant effect on determining the resonance frequency of the structure. The thickness is varied for different values, and its effect on the resonance frequency is observed. The substrate thickness is increased up to 1mm with step size of 0.2mm and the structure simulated for those thickness values.

Table 4: Resonance frequency of a square loop FSS structure ε_r=11.9, h_p=35µm, w=10mm

g	Resonance Frequency (GHz)			
	h_s=0.2mm	h_s=0.4mm	h_s=0.6mm	h_s=0.8mm
0.5	13.12	9.79	8.12	7.1
1	13.82	10.64	9.04	7.97
1.5	14.23	11.32	9.63	8.58
2	14.63	11.85	10.27	9.18
2.5	15.21	12.51	10.87	9.85
3	16.03	13.36	11.71	10.6

For all different patch side lengths, thicker substrates cause lower resonance frequencies. For a conducting patch width of 1mm the resonance frequencies are 1.82GHz and 7.97GHz, respectively. For the conducting patch width of 3mm the resonance frequency is decreased to 5.43GHz when the thickness is increased to 0.8mm from 0.2mm.

3.1.4 *Effect of permittivity values (ε_r) to S_{11}-parameter*

As mentioned before, planar frequency selective surfaces consist of a dielectric layer under the radiating patch so that it has an effect on resonance frequency of the structure, as well. Different substrates with permittivity values of 11.9, 7.9, and 4.4 are considered and evaluated; these permittivity values correspond to the materials silicon, mica and FR4, respectively.

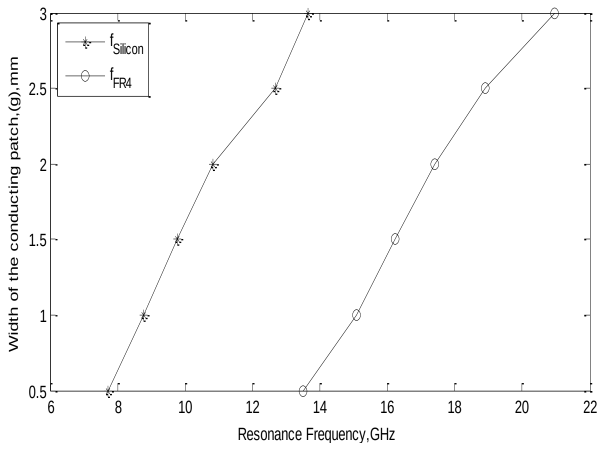


Figure 4: The effect of the permittivity values to the resonance frequency of a square loop FSS structure h_s=1mm, h_p=35µm, w=10mm for both FR4 and Silicon

The permittivity effect on resonance frequency can be observed from Figure 3 and Figure 4. As seen in both figures, these three substrates are evaluated for the same geometry. For a conducting patch width of 0.5mm, the FSS constructed with FR4 (4.4), mica (7.9) and silicon (11.9) has a resonance frequency of 13.5GHz, 7.97 GHz and 7.71 GHz, respectively. For the conducting patch width of 3mm the resonance frequency increased to a value of 20.96 GHz, 11.73GHz and 13.65 GHz, for FR4, mica and silicon, respectively. All those increments observed for all values of conducting patch width so it is concluded that the larger permittivity values result in a decrement in the resonance frequency.

3.2 *Bandwidth enhancement via changing permittivity*

The studies in literature emphasize that the most important parameter for increasing the bandwidth is related with material properties. In this manner, a FSS structure is evaluated with different material properties which of those have permittivity values in between 4.4 and 11.9. The results of S_{11} parameters are presented in Figure 5.

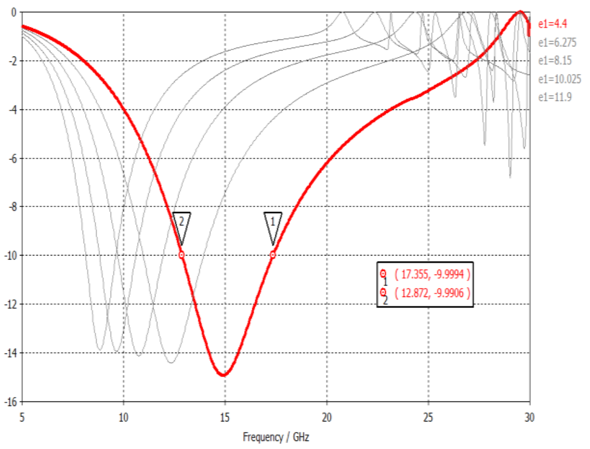


Figure 5: The effect of the permittivity values to the bandwidth of a square loop FSS structure h_s=1mm, h_p=35µm, w=10mm for different permittivity values.

As shown in figure, the lower permittivity values cause larger bandwidth, and the largest bandwidth is achieved at a permittivity of 4.4. It should also be noted that the return loss decreases in terms of dB when the permittivity value decreases. For all proposed materials demonstrated in Figure 5, the bandwidth is calculated with its upper and lower frequencies and the results are shown in Table 5.

Table 5: Bandwidth of a square loop FSS structure for different substrates, h_p=35µm, h_s=1mm, w=10mm

ε_r	11.9	10.02	8.15	6.275	4.4
f_{r_upper} (GHz)	9.63	10.6	11.94	13.93	17.35
f_{r_lower} (GHz)	8.13	8.81	9.69	10.94	12.87
BW (GHz)	1.5	1.79	2.24	2.99	4.48

Different permittivity values are considered in the table and the lower bandwidth of 1.5 GHz is observed with silicon having 11.9 permittivity values. The bandwidth is increased to 1.79 GHz for Arlon AR1000 (with a relative permittivity of 10.02). The permittivity decrement causes an increment in the bandwidth and with FR4, a bandwidth of 4.48GHz is achieved.

3.3 Transmission and shielding characteristics

Transmission and shielding characteristics (the S_{21} parameter) are evaluated in the given frequency ranges for square loop FSSs in proposed geometries. Just to clarify, an example can be given with the application area. If a radome design is considered, generally electromagnetically transparent radomes are desired. To achieve this, the relevant structures have to transmit the electromagnetic signals completely. In a physical expression, a S_{21} parameter of above -10dB corresponds to a structure which behaves approximately transparent to the radar. Transmission and shielding characteristics (S_{21}) will be analyzed in the following section for different physical properties of FSS.

3.3.1 Variation of the S_{21} parameter with the physical parameters variation

The changes in S_{11} parameters with the changes in physical properties were shown in previous sections, and S_{21} will be considered in this part. What happens to the S_{21} parameter with the change in conducting patch width denoted as g? In order to analyze this, FSS structure constructed from silicon with a thickness of 1 mm and a side length of 13mm is considered, and the results are shown in Figure 6.

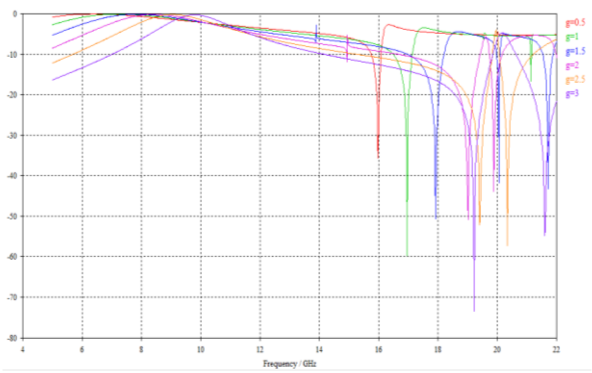


Figure 6: S_{21} parameters for different g values for a FSS with w=13mm, h_s=1mm, h_p=35mm and ε_r=11.9

The S_{21} parameter remained in the interval of 0 to -20 dB between the frequencies of 4GHz to 16GHz. After 16 GHz at several points, the S_{21} parameter reduced down to -70 dB. It can be concluded that the transmission occurs between 7GHz and 14GHz. After 14GHz, there are few points that this structure acts as a shield, since S_{21} decreases below -10dB. When the side length is decreased to the 10mm, and substrate is changed to loss-free mica; the S_{21} parameters change drastically and for a significant part of the frequency range, it remained below -10dB as in Figure 7.

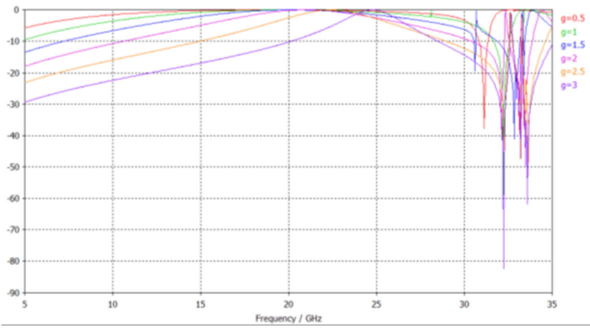


Figure 7: S_{21} parameters changes with different g values for a FSS with w=10mm, h_s=1mm, h_p=35mm and ε_r=7.9

In order to show the effect of the thickness of the substrate, a square loop FSS having a side length of 10 mm and conducting patch width of 1mm is simulated. The results, which are demonstrated in Figure 8, show that except at a frequency of 21GHz the S_{21} parameter varies between 0 and -10dB, mostly closer to -10dB. The electromagnetic waves, which are incident on the structure, are mostly transmitted with an insertion loss of almost 10dB regardless of the substrate thickness value.

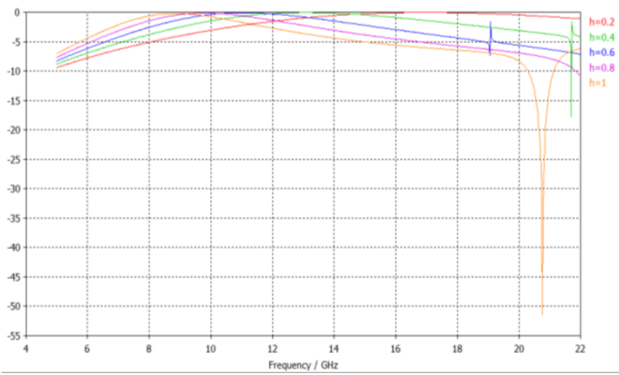


Figure 8: S_{21} parameters changes with different h_s values for a FSS with w=10mm, g=1mm, h_p=35mm and ε_r=11.9

When the previous structure is simulated for a FSS with a side length of 13mm, the S_{21} parameter increased for almost every point as in Figure 9, except 16.9GHz, 18.3GHz and 19.9GHz for the substrate thicknesses of 1mm, 0.8mm and 0.6mm, respectively.

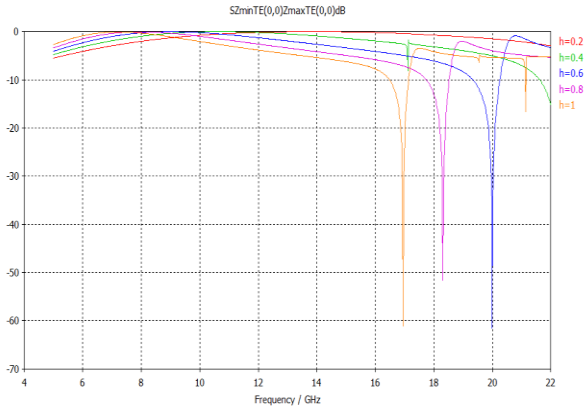


Figure 9: S_{21} parameter changes with different h_s values for a FSS with w=13mm, h_p=35mm, g=1mm and ε_r=11.9

If the side length of the structure varies, the S_{21} parameter changes slightly. The insertion loss comes closer to -10dB for nearly every thickness value. Shielding effect is observed at 3 different frequencies at 16.9GHz, 18.3GHz and 19.9GHz for h_s=1mm, h_s=0.8mm and h_s=0.6mm, respectively.

4 CONCLUSIONS

To conclude up, a square loop frequency selective surface is analyzed in terms of its *S* parameters with the change of its physical and material properties. These analysis showed that the larger side length of square loops cause lower resonance frequencies. The conducting patch width has an additive effect on resonance frequency. The substrate thickness affects the resonance frequency as well, since higher thicknesses cause lower frequencies. Besides physical dimensions, material properties have a significant effect on resonance frequency. The higher permittivity values cause lower resonance frequencies. The effect of permittivity is not only limited with the resonance frequency but also important in determining the bandwidth. The results showed that with lower permittivity values larger bandwidth is achievable. The bandwidth is increased from 1.5GHz to 4.48GHz by changing the substrate from silicon to FR4. The transmission and shielding characteristics are also evaluated in the proposed study. As a future work, the study may be extended to other geometries and may be applied for specific applications.

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