A Dual Layer Frequency Selective Surface Reflector for Wideband Applications

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Abstract. *A dual-layer, bandstop frequency selective surface (FSS) is presented in this paper for wideband applications. Each layer uses patch type FSS with slots for miniaturization and are cascaded with an air gap in between. The low-profile FSS with unit cell dimension on the order of $0.2\lambda_0 \times 0.2\lambda_0$ provides transmission coefficient below $-10\,dB$ in the frequency range of 4-7 GHz with 56% bandwidth. The FSS exhibits a nearly linear phase variation with frequency in the operating band and can be used as a substrate below planar wide band antennas with bidirectional radiation for enhancing its gain, directivity in the broadside direction as well as shielding it against nearby conductive surfaces such as metal cases, other printed antennas. Detailed design method, equivalent circuit analysis and measurement results of the FSS are presented in this paper.*

Keywords

Frequency Selective Surface, reflection phase, bandstop, wideband, reflector

1. Introduction

Frequency Selective Surfaces (FSSs) are wireless counterpart of traditional filters that are used in radio frequency (RF) circuits. FSSs are periodic arrays of metallic patch or apertures on a dielectric slab and are used for fully reflecting (patch) or transmitting (apertures) radio waves from antenna at specific frequencies or band of frequencies [1]. Since introduction, FSS is being used in radome, subreflector, polarizer, satellite transponder etc. [1–3]. In recent years, researchers have become interested in designing wideband FSS structures of both bandpass and bandstop response for their applications in gain or directivity enhancement of broadband, omni-directional antennas such as slot antennas when used as their substrates (bandstop) or superstrates (bandpass) [4–9]. Such enhancements are also possible with simple metallic reflectors placed at quarter wavelength spacing from the antenna, but their functioning is optimal over a smaller bandwidth. Moreover FSS also provides shielding to the antenna against nearby conductive

elements [6]. Gain and bandwidth enhancement of a dual band U slot patch antenna using loop shaped FSS as substrate was proposed by Hsing-Yi Chen and Yu Tao [5]. A high gain edge fed patch antenna was designed by W. Yang et al. [9] where gain of the antenna and its array was enhanced over a wide bandwidth using artificial magnetic conductors (AMC).

In general multiple FSS layers are cascaded to achieve multiband or broadband response [10–13]. FSS layers with distant frequency bands are used to achieve multiband response [10] whereas those with closely spaced resonating frequencies lead to higher order wideband response. In case of wideband FSS, introduction of air gap between the layers reduce their mutual coupling leading to a significant reflection over the bandwidth. Cascaded FSS screen with a nearly linear variation of transmission or reflection phase over a wide bandwidth is very useful in enhancing radiation properties of antennas with bidirectional radiation such as wide slot antennas as was discussed in [6].

In this paper, the design of a dual-layer, reflective FSS is proposed. The proposed FSS gives a transmission coefficient below –10 dB over a wide frequency range of 4-7 GHz and thus works as a good reflector offering 56% bandwidth. The FSS layers have been simulated with ANSYS HFSS for different parameters. Performance of the cascaded FSS has been experimentally verified. An equivalent circuit model of the FSS is also presented and analyzed using ADS simulator. The FSS can be used as a reflector with almost linear phase variation with frequency in any wideband antenna as a substrate for its performance improvement and at the same time shielding the antenna from any nearby conductive element.

2. Design of the FSS

A three dimensional view of the proposed dual-layer FSS with complete geometry is shown in Fig. 1(a). The proposed FSS is composed of two patch type layers cascaded with air gap in between. Patch type FSS is chosen to achieve the response of a bandstop filter and thus good reflection characteristics in the frequency band of 4-7 GHz. In layer I, a square patch of 10 mm × 10 mm is used with
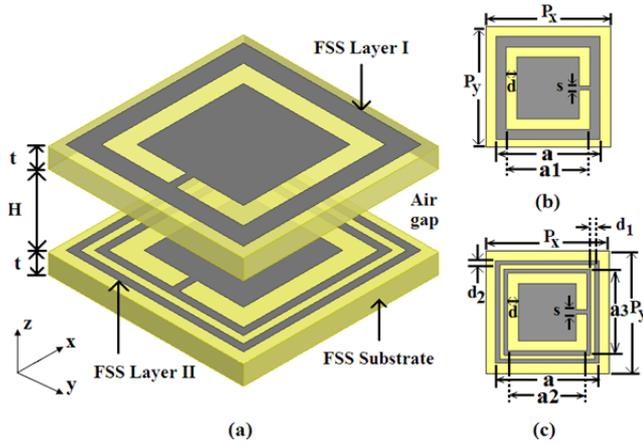
Fig. 1. (a) 3-D view of the cascaded FSS. Unit cell of the schematic of the (b) FSS Layer I (c) FSS Layer II (all dimensions are in mm).

$P_x=P_y$	a	a_1	a_2	a_3	d	d_1	d_2	g	s
11	10	8	7.6	8.4	1	0.4	0.4	0.4	1

Tab. 1. Unit cell dimensions of FSS layers (in mm).

a slot cut on it with the shape of a split ring to cover 5-6 GHz band with resonance at 5.5 GHz. Unit cell geometry of the FSS layer I is shown in Fig. 1(b). The slot is cut to reduce resonating frequency of the patch (discussed in the next section) as because without a slot it resonates at a much higher frequency. The slot length a_1 is determined by the following equation [2]:

$$Slot\ length = \frac{c_0}{4 \cdot f \cdot \sqrt{(\varepsilon_r + 1)/2}} \quad (1)$$

where c_0 stands for velocity of light in free space $(3\times10^8$ m/s), f is the resonating frequency (5.5 GHz) and ε_r is relative permittivity of the dielectric used and in the proposed design FR4 (glass-epoxy) is chosen as substrate in both the layers and $\varepsilon_r = 4.4$. The substrate thickness is $t = 1.2$ mm. The FSS layer II whose unit cell is shown in Fig. 1(c) is designed to achieve two stop bands covering 4-5 GHz and 6-7 GHz and resonances near 4.5 GHz and 6.5 GHz, respectively. For 6-7 GHz a similar design of patch is chosen as layer I and the slot length a_2 is calculated using (1) for 6.5 GHz. A square loop shaped patch is chosen for the 4-5 GHz band and is located surrounding the square patch. Length of the square loop a is also selected using (1) for 4.5 GHz. After obtaining the values, a detailed parametric analysis was carried out (discussed in the next section) to obtain the desired response and the dimensions of unit cells of FSS layer I and II are given in Tab. 1. It can be seen, horizontal and vertical periodicities of unit cells i.e. P_x and P_y for both the layers are kept same and $P_x = P_y$. An air gap of H mm is maintained between the layers of FSS to achieve the overall transmission coefficient well below –10 dB and to achieve an almost linear variation of reflection phase with frequency in 4-7 GHz.

3. Characteristics of the FSS Layers and Parametric Analysis

The full wave EM simulation of individual FSS layers and the cascaded FSS has been carried out using finite element method based ANSYS HFSS to calculate their transmission coefficients and reflection phase response. During simulation the FSS has been assumed as infinite periodic structure and four sides of the unit cell are set to periodic boundary conditions (PBC). Finally the structure is excited with a plane wave using Floquet ports with the electric field (**E**) oriented along Y axis (Fig. 1) that is vertical polarization. Normalized transmission coefficient (dB) for the FSS layer I is shown in Fig. 2(a) for different values of the slot gap s. The study shows that with reduction in the gap, the resonating frequency shifts downward. With a reduction in gap s, the current path length in the patch increases as can be seen from surface current distribution in Fig. 3(a) and this increases effective wavelength that led to a reduced resonating frequency.

For the FSS layer II, normalized transmission coefficient (dB) for different values of spacing d_1 between the patch and loop is shown in Fig. 2(b). As can be observed
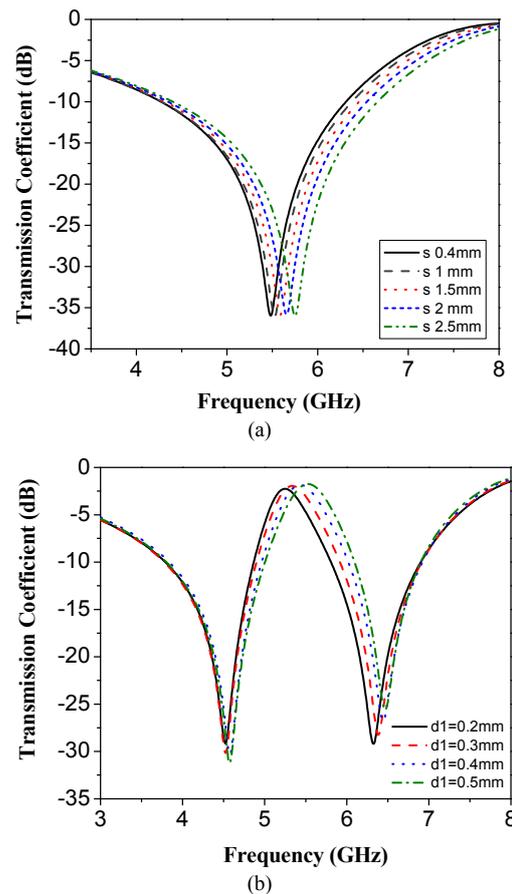
Fig. 2. Simulated transmission coefficient with parametric study of the (a) FSS layer I (for different s mm), (b) FSS Layer II (for different d_1 mm).
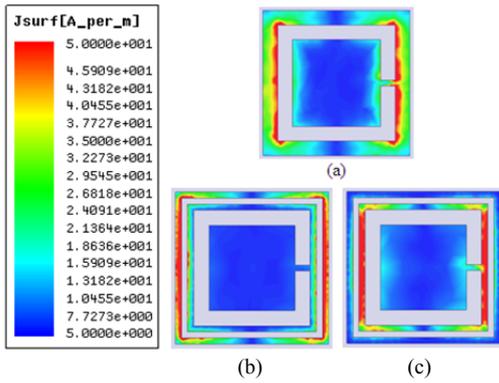
Fig. 3. Surface current (A/m) on FSS (a) Layer I at 5.48 GHz, Layer II at (b) 4.58 GHz and (c) 6.45 GHz.

(a)

(b)
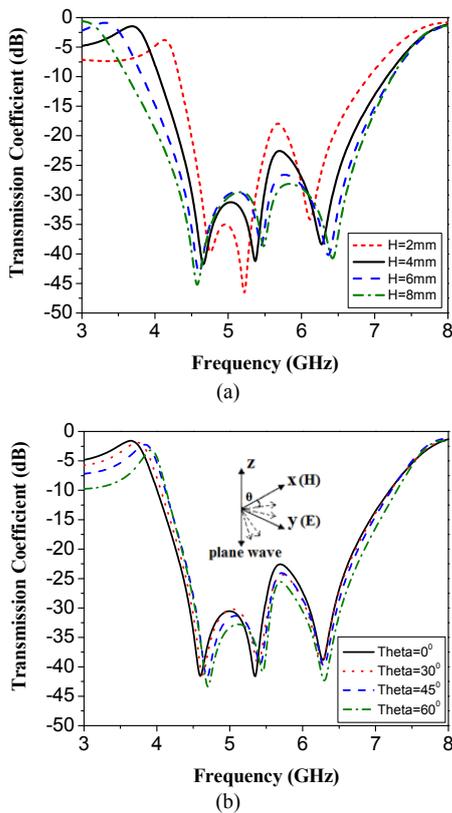
Fig. 4. Simulated transmission coefficient of the cascaded FSS for (a) different gap H, (b) different incidence angles of plane wave and $H = 4$ mm.
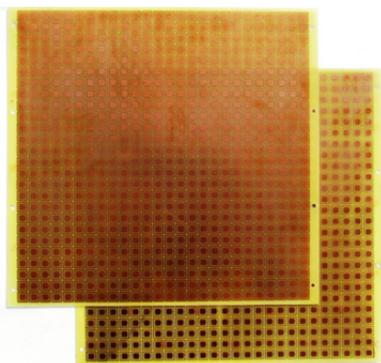
Fig. 5. Fabricated prototype of the cascaded FSS (676 elements each).

from Fig. 2(b), the FSS layer II is a dual band FSS with their resonances near 4.5 GHz and 6.5 GHz. The variation of spacing d_1 does not have significant impact on the transmission coefficient except a very small shift in the operating frequency band for the square loop shaped FSS. Surface current on unit cell of the FSS layer II shows that at 4.58 GHz the current mainly flows on the square loop FSS whereas at 6.45 GHz significant current flows around the slot on the square patch.

Simulation results for transmission coefficient of the cascaded FSS is shown in Fig. 4(a) for different values of the air gap H mm and dimensions as mentioned in Tab. 1. All simulations are carried out for normal incidence of plane wave. The air gap is used to reduce the coupling between two FSS layers and to keep the transmission level well below −10 dB. As can be observed from Fig. 4(a) increasing air gap reduces the transmission as well as increases the bandwidth. The dual layer FSS is then simulated for different incidence angles of plane wave theta (θ) in the TE (Transverse Electric) plane keeping $H = 4$ mm. As can be seen from Fig. 4(b) transmission response of the proposed FSS is not significantly affected with change in angle of incidence even upto 60°.

A fabricated prototype of the cascaded FSS is shown in Fig. 5 for $H = 4$ mm with 676 elements each having dimensions as mentioned in Tab. 1. Transmission response of the FSS is measured with a signal generator, two standard gain horn antennas with the FSS placed in between and a power meter. Simulation and measurement results for $H = 4$ mm is given in Fig. 6(a) which shows 56% measured

(a)

(b)
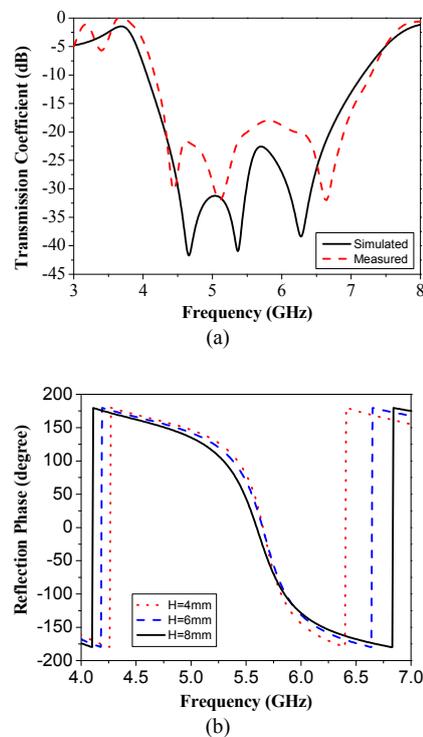
Fig. 6. (a) Simulation and measurement results for transmission coefficient of cascaded FSS of dimensions mentioned in Tab. 1 and $H = 4$ mm. (b) Reflection phase response of the cascaded FSS for different H mm.

transmission bandwidth (−10 dB) with respect to centre frequency in comparison to a simulated value of 54%. The proposed design also gives a nearly linear variation of reflection phase with frequency over the band of interest as shown in Fig. 6(b) for different values of air gap H and it can be observed that increasing air gap increases this bandwidth. Such variation of phase makes the FSS useful for gain and directivity enhancement of antennas with bidirectional or omni-directional radiation over a wide frequency band [6].

4. Equivalent Circuit Model

An equivalent circuit for unit cell of the dual layer FSS is shown in Fig. 7. The patch with slot in the layer I is modeled as a series combination of inductor L_1 and a capacitor C_1 whereas a parallel combination of two such LC resonators L_2, C_2 and L_3, C_3 represents the layer II for slot loaded patch and loop shaped FSSs respectively. All the FSS structures are modeled as series LC resonators as all of them are patch type FSS and exhibit bandstop filter response [1].

As can be seen from Fig. 3, for the two slot loaded patch type FSSs in the layer I and II, the region beside slot in the patch allowing current to flow accounts for the inductors L_1, L_2 and the gap between two successive patches accounts for the capacitors C_1, C_2. Similarly, for the loop shaped patch, the two sides of the loop through which the induced current flows as shown in Fig. 3(b), represents the inductor L_3 and the gap between two consecutive loops along which the electric field is oriented, accounts for the capacitor C_3. These LC values can be calculated using the following equations (2) and (3) as presented in [14].

$$C = \varepsilon_0 \varepsilon_{\text{eff}} \frac{2P}{\pi} \ln\left(\frac{1}{\sin\frac{\pi m}{2P}}\right), \qquad (2)$$

$$L = \mu_0 \mu_{\text{eff}} \frac{b}{2\pi} \ln\left(\frac{1}{\sin\frac{\pi w}{2b}}\right). \qquad (3)$$

Here m is spacing between consecutive patches, ε_0 (free space permittivity) $= 8.85 \times 10^{-12}$ F/m, ε_{eff} (effective permittivity) $= (\varepsilon_r + 1)/2 = 2.7$ and P is periodicity of the patch whereas μ_0 (free space permeability) $= 4\pi \times 10^{-7}$ H/m, μ_{eff} (effective permeability) $= (\mu_r + 1)/2 = 1$, b is length of the inductors, i.e. length of the slots and w is width of the inductors. The above mentioned parameters required to calculate the LC values corresponding to the patches in both the layers are given in Tab. 2 in terms of unit cell dimensions (given in Tab. 1).

Parameter	Layer I patch	Layer II patch	Layer II loop
P	$P_x = P_y = 11$ mm	$P_x = P_y = 11$ mm	$P_x = P_y = 11$ mm
m	$P - a = 1$ mm	$P - a_3 = 2.6$ mm	$P - a = 1$ mm
w	$(a - a_1)/2 = 1$ mm	$(a_3 - a_2)/2 = 0.4$ mm	$2d_2$
b	$a_1 = 8$ mm	$a_2 = 7.6$ mm	$P_x = P_y = 11$ mm

Tab. 2. Parameters used for LC calculation.
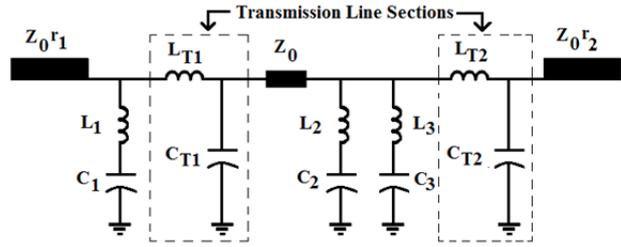
Fig. 7. Simple equivalent circuit model for FSS unit cell.
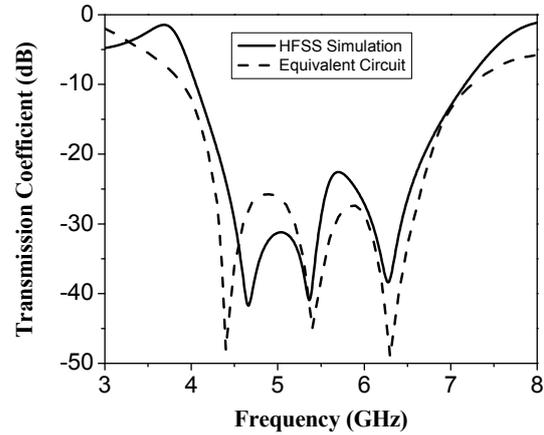
Fig. 8. Transmission coefficient of the FSS using HFSS and circuit model.
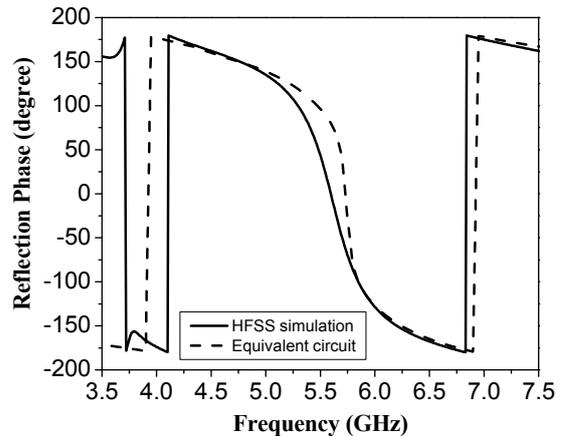
Fig. 9. Reflection phase of the FSS using HFSS and circuit model.

It can be observed from Tab. 2 that for L_3 corresponding to square loop FSS, width of the inductive strip is taken twice the width d_2 and the reason is in an array of square loop FSS, for the induced electric field along two closely spaced sides of the loop, effective width of the inductive strips become $2d_2$ as mentioned in [15–17].

In the circuit, the dielectric substrates in FSS layer I and II are modeled as transmission line sections with series inductors L_{T1}, L_{T2} and shunt capacitors C_{T1}, C_{T2}. Characteristic impedance of this transmission line is assumed to be $Z_0/\sqrt{\varepsilon_r}$ where ε_r is relative permittivity of the dielectric (4.4 for FR4) and Z_0 is free space wave impedance (377 ohms). The values of L_T and C_T can be calculated from the Telegrapher's model for TEM transmission lines using following equations (4) and (5).

$$L_{T1} = L_{T2} = \mu_0 \mu_r t \; , \tag{4}$$

$$C_{T1} = C_{T2} = \varepsilon_0 \varepsilon_r t \; . \tag{5}$$

Here t is substrate thickness = 1.2 mm for both the layers. Free spaces on both ends of the cascaded FSS are modeled here as semi-infinite transmission lines with characteristic impedances of $Z_0 r_1$ and $Z_0 r_2$ respectively where r_1 and r_2 are the normalized source and load impedances and for free space $r_1 = r_2 = 1$. The air gap between FSS layers is also represented by Z_0.

L_1	C_1	L_2	C_2	L_3	C_3	L_{T1}= L_{T2}	C_{T1}= C_{T2}
2.62 nH	0.326 pF	3.79 nH	0.169 pF	4.7 nH	0.326 pF	1.51 nH	46.728 fF

Tab. 3. Inductor and capacitor values for the circuit.

The proposed equivalent circuit was simulated using ADS (Advanced Design System) with the LC values provided in Tab. 3 for transmission coefficient and the result is shown in Fig. 8 for comparison with the results obtained from HFSS simulation. It can be seen that circuit simulation matches well with the EM simulation except a little difference in the lowest frequency corresponding to square loop in layer II. While estimating the value of L_3, two closely spaced adjacent sides of the loops have been considered to contribute for the inductance and the width is taken as $2d_2$ neglecting the spacing between them [15–17]. This approximation accounts for the difference in lowest resonating frequency. Moreover, changing the air gap H between two FSS layers is difficult to model in the equivalent circuit which also accounts for the difference in transmission response achieved from circuit model and HFSS simulation. Reflection phase response obtained from EM simulation and circuit model analysis is shown in Fig. 9 for comparison and they matches well each other only with a small change due to the reasons stated above.

Parameter	Ref[18]	Ref[19]	Proposed
Frequency band	8-13 GHz	8-11 GHz	4-7 GHz
−10dB bandwidth	45%	32%	54%
Number of layers	1	2	2
Layer spacing (mm)	NA	7.43 ($\lambda_0/4$)	4 ($\lambda_0/13$)
Unit cell (mm)	20×20	13×13	11×11
Angular stability	30°	-	60°
Reflection phase	-	-	Linear
Technology used	Fractal	Cascading	Cascading

Tab. 4. Comparison of the proposed design with previous designs.

A comparison of the proposed design and its performance with some previous designs [18], [19] is presented in Tab. 4. It can be seen that the proposed design is compact and gives a wider bandwidth than the structures in [18] and [19] but with two layers of FSS unlike that in [18]. The proposed FSS shows better angular stability than [18] though it is polarization dependent and in terms of spacing between the layers it is low profile in comparison to [19].

Novelty of the proposed FSS is its compactness ($0.2\lambda_0 \times 0.2\lambda_0$ for the center frequency), low profile ($0.1\lambda_0$) with better angular stability upto 60° and almost linear variation of reflection phase with frequency in the desired band.

5. Conclusions

In this paper, design procedure and analysis of a broadband, reflective FSS operating in the 4-7 GHz band is presented. The FSS is composed of two layers with substrate thickness of $0.02\lambda_0$ and an air gap of $0.1\lambda_0$ (λ_0 is the wavelength corresponding to the center frequency of 5.5 GHz) leading to a low profile design. The proposed design provides −10 dB bandwidth of 56% with high reflectivity as well as stable performance for different angles of incidence. An equivalent circuit model for the FSS is presented and analyzed which matches well with the EM simulation result. Measurement result for the FSS is given in the paper that confirms the simulated one. The proposed FSS gives a nearly linear phase variation over the frequency band which makes it useful for enhancing radiation properties such as gain, directivity, front to back ratio of the antennas with omni-directional or bi-directional radiation (slot antennas, CPW antenna) over a wide bandwidth when used as a reflector.

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