A Cascaded Tunable Wide Stop Band Frequency Selective Surface with High Roll-off Band Edge

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Abstract. A three-layer wide-band reflective Frequency Selective Surface (FSS) reflector with a high roll-off band edge is proposed in this paper. Each layer of the structure is patch type FSS. The proposed FSS has merits of wide-band response over S band and lower C band with bandwidth of 3.6 GHz for transmission < –10 dB with 94% bandwidth and significant stability for different incident angles up to 40 degree. The polarization insensitivity of the FSS also added an extra dimension of the structure. The simulation process as well as the experimental measurement process and ECM (equivalent circuit model) analysis of the FSS have been done. The good agreement in simulated, measured and ECM results verifies the wide stop band for the proposed FSS. The tunable and switchable transmission behavior of the FSS for variation in width of the internal air gap and lateral sliding of the middle layer of the structure respectively are also presented here.

Keywords
Frequency Selective Surface, reflector, wide stop band, roll off, cascade structure, incidence angle stability, polarization insensitivity, equivalent circuit model, tunable and switchable transmission coefficient

1. Introduction

Frequency Selective Surface is one type of spatial filter used in radio frequency. It is an arrangement of two-dimensional periodic array of metallic patches on a dielectric substrate or apertures with in a metallic sheet. It may reflect back (in case of patch type) or allow to pass (in case of aperture type) certain band or bands of radio frequencies (RF)[1], [2]. Generally they are widely used in various microwave systems like antenna, radome, sub reflector, polarizer, satellite transponder etc [3]. The wide band characteristics (may be band pass or band stop) provided by the FSS are desirable in some applications as it may enhance the gain and directivity of broadband antennas [4–8] when it is incorporated with the antenna. To improve the use of several antennas with different operating frequencies in multifunctional system [9], [10] wide band FSSs are used.

In recent years, research on designing of wide band FSS with wide incidence angle and polarization independence is going on. Besides wideband frequency behavior improvement of selectivity characteristics is one of noticeable demands in that scenario. In [11] the authors prescribed multilayer absorbers and FSS to achieve UWB response. In [12] authors proposed a multilayer FSS (four layers) to improve the gain of a UWB antenna. In [13] authors prescribed three layers of patch type FSS and an ultra wide stop band response is achieved. The roll off determines the selectivity of the operating band. Another type of wide band stop FSS is proposed in [14] by introducing the air spacing between two two-dimensional layers but in that case also out of band response is not so good. A single layer UWB FSS is proposed in [15] where the simulated operating band is 4.6 GHz–12 GHz. But in all the cases roll off of higher and lower band edge is not good enough. To improve the roll off of operating bandwidth different techniques are followed in various research works [16–18]. In [16] a three dimensional band pass FSS formed by cascaded structure of 2D array of shielded microstrip lines with sorted via to ground with multiple transmission zeros has been presented and wide out-of-band rejection in frequency behavior has been recorded. In [17] an FSS with unit cells included with mushroom-like cavity and four L-type slots etched on the top and bottom layers and sharp band edge is realized. In [18] dual layer FSS with wide-band and high selective frequency behavior has been proposed. In this FSS two layers with different unit cell structures are arranged in cascaded manner. But in these cases percentage of operating bandwidth is not very effective.

In this paper a three layer patch type FSS arranged in cascade formation is proposed. This proposed structure provides a wide stop band response with the normalized transmission coefficient below –10 dB reference level over wide frequency range of S band and lower C band (2.06 to 5.63 GHz). Thus it may be used as a good reflector with percentage bandwidth of 94%. This structure also offers a good roll off at its downward and upward cut off frequencies. As the design of patches is symmetrical in horizontal and vertical direction, it provides polarization independent transmission response for 90 degree rotational case. This proposed structure also maintains its response for different incident angles of incident wave up to 40 de-
gree. The performance of the proposed FSS is verified experimentally as well as by analyzing the equivalent circuit model (ECM).

2. Structural Description and Fabrication Process

The proposed structure consists of three single layers of Frequency Selective Surf aces (FSS) in cascade arrangement with an air gap of 14 mm in between two consecutive FSS layers. The complete geometry of unit cell structure is shown in Fig. 1(a). All the layers are patch type in design and they provide band stop properties to radio frequencies. Acrylic sheet with relative dielectric constant \( \varepsilon_r = 2.8 \), loss tangent \( \tan \delta = 0.02 \) and thickness \( h = 2.9 \text{ mm} \) is used as dielectric substrate in all of the FSS layers. To get high roll off band edge in case of FSS layer 1 and FSS layer 3, the geometries in design of patch (aluminum layer) are same and it is shown in Fig. 1(b). Fig. 1(c) shows the design geometry of FSS layer 2. All the dimensions of the proposed structures are described in Tab. 1.

This patch type FSS structure is chosen to achieve good UWB reflection characteristics in the frequency band of 2–6 GHz. In case of layer 1 and layer 3, unit cell dimension is 36 mm × 36 mm (in order of 0.2\( \lambda_0 \) × 0.2\( \lambda_0 \)), while the patch has the dimension of 32 mm × 32 mm. A square loop type slot and a square shaped slot are introduced to reduce the resonating frequency and to achieve dual stop band characteristics. In case of FSS 2 the dimension of unit cell is the same as previous two layers and the dimension of reference square patch is 28 mm × 28 mm. In this case a slot of dimension 18 mm × 18 mm is introduced. The transmission response of FSS layer 1 and layer 3 are same. When they are arranged in cascade, the transmission response has higher bandwidth and higher roll-off for both the stop bands by maintaining the resonating frequency same. Finally, for the proposed structure (as Fig. 1(a)) an UWB transmission characteristic is achieved.

To verify the transmission characteristics of the proposed FSS structure, a prototype was fabricated by using a laser cutting machine. The aluminum foil paper (used as metal layer) pasted on acrylic sheet (used as dielectric layer with \( \varepsilon_r = 2.8 \), \( \tan \delta = 0.02 \) and thickness of 2.9 mm) forms a metal-dielectric layer. The proposed three layer structure is cascaded with the help of plastic spacers and screw. The dimension of the fabricated FSS layers is 300 × 300 mm². Each of the layers contains 64 metallic patch elements. Fabricated layer 1, layer 2, layer 3 and the cascaded structures of the fabricated FSS structure are shown in Fig. 2 (a), (b), (c) and (d), respectively.

![Fig. 1.](image1.png)  
(a) Proposed unit cell structure of three layer FSS. (b) Proposed design of layer 1 and layer 3. (c) Proposed design of layer 2.

| Parameters | Values (mm) | Parameters | Values (mm) |
|------------|-------------|------------|-------------|
| h          | 2.9         | D          | 14          |
| d1         | 36          | d1         | 28          |
| d2         | 18          | d3         | 32          |
| d4         | 24          | d5         | 18          |
| d6         | 14          |            |             |

Tab. 1. Values of parameters shown in Fig. 1.

![Fig. 2.](image2.png)  
(a) Fabricated prototype of layer 1. (b) Fabricated prototype of layer 2. (c) Fabricated prototype of layer 3. (d) The proposed cascaded arrangement of 3 layered fabricated FSS.
3. Simulated and Measured Result Analysis

The full wave EM simulations of individual FSS layer and the cascaded structures are implemented by ANSYS HFSS software (based on Finite Element Method) to obtain their transmission characteristics. Below –10 dB reference level in all of the transmission characteristics curve is treated as stop band. Here all the simulations are carried out for normal incidence of the plane wave. Transmission coefficient \((S_{21})\) of FSS layer 1 & 3; layer 2 and proposed tri-layered structure as well as the reflection coefficient \((S_{11})\) are shown in Fig. 3. For layer 1 or layer 3, the transmission coefficient \((S_{21})\) with two transmission zeroes, resonated at 2.2 GHz and 5.1 GHz with percentage bandwidth of 36% and 27% respectively is obtained. For layer 2, a transmission coefficient with a single stop band at 3.8 GHz with 40% bandwidth is obtained. Here two square loops in design help to obtain these two stop bands in case of layer 1 and a single square loop in design helps to obtain a single stop band in case of layer 2. The dimensions of these square loops are taken in such a way so that the band range for layer 2 is situated in between two bands, obtained for layer 1. So when these three layers are arranged in cascade manner with maintaining an air gap \((D)\) a wide stop band of 3.60 GHz between frequency ranges of 2.03 GHz–5.63 GHz is obtained. The percentage bandwidth is increased up to 94% (measured with respect to the middle frequency of the band). Moreover, as two same designed FSS layers are cascaded (layer 1 and layer 3) a high roll-off in higher and lower cut-off frequency is achieved. Reflection coefficient \((S_{11})\) of the proposed FSS is showing that throughout the operating bandwidth all the frequencies of the incident wave is totally reflected from the proposed FSS. The roll-off in higher band edge for this transmission characteristics curve is 480 dB/GHz, whereas the roll-off in lower band edge is 180 dB/GHz, which makes the transmission characteristics more selective in nature.

As the design of unit cell for each of the layers is symmetric along \(x\)-axis and \(y\)-axis, it gives the same frequency behavior for both of the polarizations, i.e. TE and TM. For different incident angles for TE and TM mode the simulations are carried out and presented in Fig. 4(a) and Fig. 4(b), respectively. Frequency behavior is same for both TE and TM polarization of incident wave, and it can also be seen from the figures that frequency behavior of the proposed FSS has not been affected significantly up to 40°.

A parametric study is carried out for the 3 layer proposed FSS structure by varying the width of internal air gap \((D)\) between two layers. Simulated frequency behavior of the FSS for different values of \(D\) is shown in Fig. 5. It is observed clearly as value of \(D\) is increased, the resonating frequency is being shifted towards the higher frequency. This happened because of changing in coupling inductance and capacitance generated for the air gap. The resonating frequency for different widths of the air gaps are mentioned in Tab. 2.

The fabricated prototype of the 3 layer cascaded FSS is shown in Fig. 2(d). The dimensions of the unit cell patch for all of the three layers are presented in Tab. 1 which is discussed earlier. Each of the layers consists of \(8 \times 8\), total number of unit cells is 64. The prototype is fabricated by
4. Equivalent Circuit Model

The transmission behaviors of the proposed triple layered FSS are also explained hereby with the help of equivalent circuit models (ECM) which are illustrated in Fig. 9. Layer 1 and layer 3 are the same in design and illustrated by the parallel combination of two series resonant circuit formed by components \( L_1, C_1 \) and \( L_2, C_2 \). The outer square loop is modeled by \( L_1 \) and \( C_1 \) whereas the inner square loop is modeled by \( L_2 \) and \( C_2 \). The values of \( L_1, L_2, C_1 \) and \( C_2 \) are calculated using the following equations [19].

\[
L_1 = \mu_0 \frac{d_1}{2\pi} \left[ \ln \left( \frac{\csc \frac{\pi w_1}{2d}}{\csc \frac{\pi w_2}{2d}} \right) \ln \left( \frac{\csc \frac{\pi w_2}{2d}}{\csc \frac{\pi w_1}{2d}} \right) \right],
\]

\[
L_2 = \mu_0 \frac{d_3}{2\pi} \ln \left( \frac{\csc \frac{\pi w_3}{2d}}{\csc \frac{\pi w_4}{2d}} \right),
\]

\[
C_1 = \varepsilon_r \varepsilon_{r_{\text{eff}}} \left[ 0.75 \cdot 4 \cdot \varepsilon_r \frac{d_3}{2\pi \varepsilon_r} \ln \left( \frac{\csc \frac{\pi g_1}{2d}}{\csc \frac{\pi g_2}{2d}} \right) \right],
\]

\[
C_2 = \varepsilon_r \varepsilon_{r_{\text{eff}}} \cdot 4 \cdot \varepsilon_r \cdot \frac{d_3}{2\pi \varepsilon_r} \ln \left( \frac{\csc \frac{\pi g_2}{2d}}{\csc \frac{\pi g_3}{2d}} \right).\]

In these equations, \( d, d_3 \) and \( d_3 \) are periodicity of the unit cell, length of the outer loop and length of the inner loop of layer 1 and layer 3, respectively. \( w_1 \) and \( w_2 \) are width of the outer loop and width of the inner loop, respectively. \( g_1 \) and \( g_2 \) are the width of the inter gap of two outer loop and the gap between the outer loop and the inner loop, respectively.

The square loop in the middle layer is modeled by \( L_3 \) and \( C_3 \). The values of \( L_3 \) and \( C_3 \) are calculated from the following equations [20]

\[
L_3 = \mu_0 \frac{d_4}{2\pi} \ln \left( \frac{\csc \frac{\pi w_3}{2d}}{\csc \frac{\pi w_4}{2d}} \right).
\]
\[ C_3 = \varepsilon_0 \varepsilon_{\text{eff}} \frac{2d_1}{\pi} \ln \left( \csc \frac{\pi g_3}{2d_1} \right) \]  

In these equations, \( d_1, \) \( w_3 \) and \( g_3 \) are length of the square loop, width of the square loop and width of the inter gap between two adjacent square loops on the middle layer.

The dielectric substrate is also modeled as transmission line formed with \( L_{T1} \) and \( C_{T1} \) where the value of \( L_{T1} \) and \( C_{T1} \) are as follows [21]

\[ L_{T1} = \mu_0 \cdot h, \]  
\[ C_{T1} = \varepsilon_0 \varepsilon_{\text{eff}} \cdot h. \]  

In these equations, \( h \) represents the width of the substrate.

The air gap between the two layers is also modeled as transmission line formed with \( L_{T2} \) and \( C_{T2} \) where the value of \( L_{T2} \) and \( C_{T2} \) are as follows [21]

\[ L_{T2} = \mu_0 \cdot D, \]  
\[ C_{T2} = \varepsilon_0 \varepsilon_{\text{eff}} \cdot D. \]  

Here, \( D \) stands for the width of the air gap between the two layers.

For all the cases, \( \varepsilon_0 \) (free space permittivity) is \( 8.85 \times 10^{-12} \) F/m, \( \varepsilon_{\text{eff}} \) (effective permittivity of dielectric) is \( (\varepsilon_r + 1)/2 = 1.9 \) and \( \mu_0 \) (free space permeability) is \( 4\pi \times 10^{-7} \) H/m.

All the calculated values of inductances and capacitances are presented in Tab. 3. Transmission properties \( (S_{21}) \) of the equivalent circuit shown in Fig. 9 are gotten from ADS software.

The comparison of the simulated transmission characteristics \( (S_{21}) \) of the proposed FSS observed from HFSS and deduced from equivalent circuit model is shown in Fig. 10. Both of the graphs are in good agreement and verifying the simulated result of the proposed FSS.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| \( L_1 \) | 9.6 nH | \( L_2 \) | 6.3 nH |
| \( L_3 \) | 8.4 nH | \( C_1 \) | 0.196 pF |
| \( L_{T1} \) | 5.6 nH | \( C_2 \) | 0.321 pF |
| \( L_{T2} \) | 17.7 nH | \( C_{T1} \) | 0.071 pF |

Tab. 3. Values of inductors and capacitors of the ECM circuit shown in Fig 9.

A comparative study of the proposed FSS with some recently published articles of same kind of work has been presented in Tab. 4.

| Parameters | Ref[22]# | Ref[23] | Ref[24] | Ref[25] | Proposed |
|-----------|----------|---------|---------|---------|----------|
| Frequency Band | 5.9–13.4 GHz | 3.05–10.65 GHz | 40–70 GHz | 6.0–15.0 GHz | 2.06–5.63 GHz |
| Percentage Bandwidth | 87.4% | 109.4% | 54.5% | 85.7% | 94% |
| Number of layers | 3 | 2 | 2 | 2 | 3 |
| Layer spacing | 0.17 \( \lambda_0 \) | 1.1 \( \lambda_0 \) | Not mentioned | 0.1 \( \lambda_0 \) | 0.1 \( \lambda_0 \) |
| Unit cell dimensions | 0.2 \( \lambda_0 \times 0.2 \lambda_0 \) | 0.3 \( \lambda_0 \times 0.3 \lambda_0 \) | 0.34 \( \lambda_0 \times 0.34 \lambda_0 \) | 0.5 \( \lambda_0 \times 0.5 \lambda_0 \) | 0.2 \( \lambda_0 \times 0.2 \lambda_0 \) |
| Incidence angle stability | Up to 30 degree | Up to 30 degree | Up to 30 degree | Not mentioned | Up to 40 degree |
| Maximum insertion loss | NA | –43 dB | –55 dB | –45 dB | –70 dB |
| Minimum insertion loss | NA | –15 dB | –16 dB | –15 dB | –23 dB |
| Roll off in lower band edge | 5 dB/GHz* | 80 dB/GHz* | 23 dB/GHz* | 75 dB/GHz* | 180 dB/GHz |
| Roll off in higher band edge | 12 dB/GHz* | 10 dB/GHz* | 6.4 dB/GHz* | 8 dB/GHz* | 480 dB/GHz |
| Technique used | Cascade | Cascade | Cascade | Cascade | Cascade |
| Tunable and switchable | No | No | No | Yes | Yes |

Tab. 4. Comparison table of the proposed work with some previous same kind of works.

[* Roll off of the lower band edge and higher band edge of the previous works is not mentioned in their article. These roll offs are calculated from their transmission characteristics curves.
# in this article, 3dB bandwidth of the pass band has been presented in the article where as in rest of all cases –10 dB bandwidth has been presented.]
It can be easily seen the proposed design has good compactness with respect to the previous designs (as unit cell dimension is 0.2 λ₀ × 0.2 λ₀). Percentage bandwidth is also very good enough. Insertion loss throughout the operating band is better than other reported works (maximum insertion loss -70 dB and minimum insertion loss is -23 dB) and also huge roll-off in lower and higher band edge have been achieved. This type of huge roll-off gives the structure more selectivity of its operating band which is not shown in case of other works. The proposed FSS also has good incident angle stability (up to 40 degree) and polarization independency. Tunability and switchability in frequency behavior offer the proposed FSS structure another dimension of novelty.

5. Conclusion

In this paper the design procedure and the analysis on transmission characteristics of an FSS with wide stop band characteristics in the frequency range of 2.06 GHz to 5.63 GHz is presented. The proposed structure contains three layers of patch type FSS arranged in cascade with a certain air gap in between two consecutive layers leading to a low profile design. The proposed design provides bandwidth of around 94%. Moreover the structure has a good roll-off in higher and lower cut-off frequencies in its transmission characteristics. As the designs of patch elements in each of the layers are symmetric with respect to x and y axes, transmission characteristics remain same for 90 degree rotation of the FSS. Measured data significantly follows the simulated result. The wideband characteristics of this proposed FSS may be useful in enhancing the radiation properties of an antenna with wide band operating frequency. The FSS may also be useful in a dichroic reflector system.

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