Modelling of a Polarization Insensitive UWB FSS with Band Stop Response

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Abstract. This paper presents a compact ultra-wideband frequency selective surface (FSS) with band stop response. The proposed single layer FSS is printed on FR-4 substrate with a unit cell periodicity of $0.138\lambda_0 \times 0.138\lambda_0$ corresponding to its lowest operating frequency. The developed FSS exhibits stable response for plane waves with normal and oblique incidence with TE and TM polarization for angles varying from 0° to 60°. The FSS offers –10dB bandwidth of 141 % covering the entire ultra-wideband frequency range from 2.39 GHz to 13.67 GHz. The structural parameters are optimized, and an equivalent circuit is modelled to analyze the performance of FSS. The simulated results are validated by the measured values.

Keywords
Frequency selective surface, periodic structure, ultrawideband, bandstop, wireless communication

1. Introduction

The frequency selective surfaces (FSS) are 2D or 3D periodic structures exhibiting pass band or stop band filter response. Basic configurations of FSS with design concept are considered by Munk [1]. The periodic structures can be designed as spacial filters to select or reject a set of frequencies. A periodic structure with narrow band acting as a partial reflecting surface was reported by the authors [2]. The filter response of FSS differs from microwave filters in terms of its dependency in design structure, incident angle and polarization of the electromagnetic signal. Extensive survey on various FSS designs were investigated [3], [4]. Narrow, wide and ultrawideband nature of FSS fits them in diverse fields including radar cross section (RCS) reduction, electromagnetic shielding and antenna application. Single layer and dual layer FSS are reported in literature [5–7]. Simple circular slot FSS with active and passive components are capable of single or dual band operation [8], [9]. A quad band switchable FSS with pin diodes operating in ISM frequency range, improves the isolation between indoor wireless devices [10]. A miniaturized dual layer UWB FSS with dielectrics AD300A and AD600 separated by three parts of metallic elements consisting of rotated cross dipoles has 60° angular stability [11]. The low-profile dual layer FSS reflector [12] covers the UWB band from 3.5 to 11.45 GHz. As FSS are designed with half wavelength, the percentage bandwidth is limited and they generate grating lobes reducing the performance in the upper band. Though multilayer FSS produce broad bandwidth, they are inefficient in terms of size and cost. FSS for RCS reduction and antenna application are discussed in earlier works [13–16]. Different polarization independent UWB FSS designs were analyzed [17–22]. Single layer dual sided FSS with UWB coverage are reported with polarization independence and higher incident angle stability [23–25]. The electromagnetic behavior of FSS structures can be analyzed using tedious mathematical modelling techniques. A relatively simple approach is to develop an equivalent circuit with inductive and capacitive reactance, which characterize the electromagnetic behavior of FSS. The LC equivalent circuit models of various periodic structures are documented [26–28]. The demand for UWB FSS with stable operation in modern high-speed communications aims at designing a novel FSS structure.

In this paper, a compact novel FSS with angular and polarization stability for UWB application is presented. Compared to the available FSS in the literature, the proposed structure has maximum percentage bandwidth on a single layer design. To operate in the UWB frequency band a combination of square and circular loop with loading strips and cross dipoles are used. With the transmission response of –10 dB, the designed FSS has a stable operation in TE and TM polarization for an incident signal of variable angles up to 60°. A simple equivalent circuit model is developed to match the response of FSS design. The FSS designs were simulated using CST microwave Studio. The frequency domain solver option of CST with Floquet’s boundary conditions for unit cell geometry is chosen to compute the parametric analysis of the designed UWB FSS. The equivalent circuit values were theoretically calculated and the schematic is modelled using ADS software. The LC components of the circuit with matched terminations on either side are analyzed by tuning and the S parameter results in terms of reflection and transmission are plotted.
2. Design of the Proposed UWB FSS

The designed FSS is aimed to operate in the FCC regulation UWB frequency band ranging from 3.1 GHz to 10.6 GHz. The four main groups of FSS designs [1] were analyzed and the hybrid combinations of them are used to propose the new UWB FSS design. In this paper a single layer, compact UWB FSS with angular and polarization stability is designed. This reduces the cost and complexity of the design compared to multilayer designs. The proposed FSS structure is designed on FR-4 dielectric substrate with parameters \( \varepsilon_r = 4.4, \tan \delta = 0.025 \) and height \( h = 1.6 \) mm. The thickness \( t \) of the copper conductor is \( 0.035 \) mm.

The UWB FSS design consists of a square loop integrated with thin strips and a cross dipole convoluted circular loop to achieve ultra-wideband frequency coverage. Figure 1(a), (b) shows the top and side view of the proposed single layer unit cell FSS design. Initially a square loop with a circumference of \( \lambda \) at lower frequency of 3.1 GHz is calculated. To accommodate the upper frequency band of 10.6 GHz, a circular loop is placed at the center of the square loop. The combination of square and circular loops provides two independent bands resonating at 3.64 GHz and 11.49 GHz respectively. The branch circular loops provides two independent bands resonating at 3.64 GHz and 11.49 GHz respectively. The branch loading of the loops with four narrow strips at the middle of square edges merged the resonance bands offering a bandwidth of 7.65 GHz ranging from 2.43 GHz to 10.09 GHz of UWB band. To expand the higher frequency, two dipoles of \( \lambda/2 \) at center frequency is placed diagonally convolving with the circular loop. This improved the bandwidth to 11.28 GHz with 8 GHz as the center frequency. The optimized FSS operates within the frequency band between 2.39 GHz and 13.67 GHz. The proposed FSS unit cell has an optimized periodicity of 0.138 \( \lambda_0 \) and overall height of 0.0127 \( \lambda_0 \), where \( \lambda_0 \) is the free space wavelength at the lower cut off frequency. The design parameters of proposed UWB FSS unit cell are summarized in Tab. 1.

![Fig. 1. The geometry of proposed UWB FSS unit cell. (a) Top view. (b) Side view.](image)

| \( P \) | \( L \) | \( s \) | \( x \) | \( r \) | \( r_1 \) | \( h \) | \( t \) |
|-------|-------|-------|-------|-------|-------|-------|-------|
| 17.4  | 17    | 3     | 0.5   | 3.1   | 4     | 1.6   | 0.035 |

Tab. 1. Dimensions of the proposed UWB FSS unit cell in mm.

3. Design of the Proposed UWB FSS

The LC equivalent circuits are simple solutions to find the resonance frequency of any complex structures. The equivalent circuits for square and circular loop FSS are based on the solutions given in [26–28]. Figure 2 shows the layout of a simple printed square and circular loop FSS with period \( p \), width \( w \), side length \( d \) and the inter element gap between adjacent squares in a periodic array. The equivalent circuit of printed square or circular loop would have a series combination of lumped inductor \( L \) and capacitor \( C \) connected in shunt between the free space impedance \( Z_0 \) of 377 \( \Omega \) as in Fig. 3(a).

The reactance \( X_L \) and susceptance \( B_C \) of (1), (2) based on [26–28] are used to solve the values of \( L \) and \( C \) of the equivalent circuit:

\[
\frac{X_L}{Z_0} = \frac{d}{p} F(p, w, \lambda, \theta) \\
= \frac{d}{\lambda} \cos \theta \left[ \ln \left( \csc \left( \frac{\pi w}{2p} \right) \right) + \frac{G(p, w, \lambda, \theta)}{2} \right], \\
B_C = 4 \frac{d}{\lambda} \frac{F(p, g, \lambda, \theta) \varepsilon_{\text{eff}}}{\varepsilon_0} \\
= \frac{4d}{\lambda} \cos \theta \left[ \ln \left( \csc \left( \frac{\pi g}{2p} \right) \right) + \frac{G(p, g, \lambda, \theta)}{2} \varepsilon_{\text{eff}}. \right]
\]

Here \( \theta \) and \( \lambda \) are the angle and wavelength of the incident signal. The correction term \( G(p, w, \lambda, \theta) \) is given by

\[
0.5 \left( 1 - \beta^2 \right)^2 \left[ 1 - \frac{\beta^2}{4} \right] (A_e + A_e) + 4 \beta^2 A_e A_e \\
- \frac{\left( 1 - \beta^2 \right)^2}{4} + \beta^2 \left( 1 + \frac{\beta^2}{2} - \frac{\beta^2}{8} \right) (A_e + A_e) + 2 \beta^2 A_e A_e
\]

where \( A_e \) and \( \beta \) are

\[
A_e = \frac{1}{\sqrt{1 + 2 \rho \sin \theta - \left( \frac{p \cos \theta}{\lambda} \right)^2}} - 1 \\
\text{and} \quad \beta = \sin \left( \frac{\pi w}{2p} \right) .
\]

The reactance leading to inductance of a circular loop with the same period \( p \), strip width \( w \) and gap \( g \) of the square loop has a modified equation, as it has a variable circumference with diameter \( d \) as a function of \( \pi d \) compared to \( 4d \) in square loop. Thus, equation (1) includes an additional factor of \( \pi/4 \) for the circular loop which reduces the reactance by a factor \( d/p \). The susceptance owing to the capacitor is calculated based on two adjacent circular loops acting as the parallel plates separated by the average gap distance \( g_{se} \), effective dielectric constant of the substrate \( \varepsilon_{\text{eff}} \) and half the loop length \( \pi d/2 \). This leads to a factor
of \( \pi/2 \) in (2). The modified equations for reactance \( X_L \) and susceptance \( B_C \) of circular loops are given by (3) and (4) from which the lumped inductance \( L_1 \) and capacitance \( C_1 \) are computed:

\[
X_L = \frac{\pi d}{4} F(p, w, \lambda, \theta), \quad (3)
\]

\[
B_C = \frac{\pi d}{2} F(p, g_a, \lambda, \theta) e_{\text{eff}}. \quad (4)
\]

In (4) the average gap \( g_a \) between the circular elements is given by

\[
g_a = p - \frac{\pi d}{4}.
\]

The outer square loop and inner circular loop forms two narrow band resonances at lower and higher frequencies of UWB range. When both loops are combined the reactance and susceptance are calculated as a parallel combination of individual elements, and the two resonance curves merge together to form a wideband response with \( L_1, C_1, L_2 \) and \( C_2 \).

In the proposed FSS design the square and circular loops are loaded with four metallic strips at the middle of the square arms and two diagonal dipoles across it. This makes two additional LC pairs. The branch loading and the mutual coupling effects further expand the operational frequency band on either edge. Figure 3(b) shows the equivalent circuit of proposed UWB FSS. The values of LC pairs calculated are tuned using ADS software to match the simulated response of CST studio which also account for the coupling effects of lumped parameters.

The optimized values of equivalent LC pairs are \( L_1 = 2.3 \) nH, \( L_2 = 2.6 \) nH, \( L_3 = 2.158 \) nH, \( L_4 = 2.207 \) nH, \( C_1 = 0.17 \) pF, \( C_2 = 0.130 \) pF, \( C_3 = 0.001 \) pF and \( C_4 = 0.16 \) pF.

Figures 4(a), (b) represent the simulated transmission and reflection characteristics of square loop FSS, circular loop FSS and the proposed UWB FSS using CST studio along with their LC equivalent circuit response. The simulated results show good matching with the equivalent circuit response, except at higher frequencies above 12.5 GHz for circular loop FSS which may be due to deviation in LC value on tuning than theoretically calculated.

4. Performance Analysis of FSS

The structural parameters \( P, s, x, r_1 \) and \( r_2 \) are optimized to accomplish the ultrawideband operation. The period \( P \) of the unit cell is 17.4 mm. The length of the square loop is maintained at 17 mm and the width \( s \) is varied from 0.5 mm to 3 mm in steps of 0.5 mm. The results
show a right shift in resonance frequency with wider bandwidth. The circular loop radii \( r \) and \( r_1 \) are varied from 3 mm to 3.5 mm and 3 mm to 5 mm, respectively. Stable response with wider bandwidth is obtained at \( r = 3.1 \) mm and \( r_1 = 4 \) mm. The variation of the width of the cross dipoles and the strips \( x \) from 0.1 mm to 0.7 mm resulted in shift of the center frequency to a higher value with increase in \( x \). At \( x = 0.5 \) mm the center frequency is 8 GHz with a stable response and wider bandwidth. The theoretical results and the investigation of the optimization plots reveal that the bandwidth and center frequency of the FSS is influenced with the periodic cell size and structural dimensions.

The optimized reflection and transmission response of the proposed UWB FSS for TE and TM mode are plotted in Fig. 5. The absolute value of \( S_{11} \) in log magnitude format for TE and TM mode is close to zero for the entire frequency band as required. The transmission coefficient \( S_{21} \) shows a value of \(-50.58\) dB at 8 GHz frequency and is below \(-10\) dB from 2.39 GHz to 13.67 GHz achieving UWB operation. The phase of the reflection response varies linearly from \(-180^\circ\) to \(180^\circ\), within the entire frequency band from 1.389 GHz to 15.144 GHz as depicted in Fig. 6.

The optimized performance of the proposed unit cell in terms of transmission and reflection coefficients is shown in Fig. 5. The reflection phase performance of the proposed unit cell is depicted in Fig. 6. The optimized reflection and transmission response of the proposed UWB FSS for TE and TM mode are plotted in Fig. 5. The absolute value of \( S_{11} \) in log magnitude format for TE and TM mode is close to zero for the entire frequency band as required. The transmission coefficient \( S_{21} \) shows a value of \(-50.58\) dB at 8 GHz frequency and is below \(-10\) dB from 2.39 GHz to 13.67 GHz achieving UWB operation. The phase of the reflection response varies linearly from \(-180^\circ\) to \(180^\circ\), within the entire frequency band from 1.389 GHz to 15.144 GHz as depicted in Fig. 6.

The response of the FSS resembles the characteristics of a band stop filter at 8 GHz with a bandwidth of 5.2 GHz at an attenuation level of 20 dB.

The proposed UWB FSS is also analyzed for polarization and angular stability of the incident signal. The simulated results of transmission characteristics for various incident angles are plotted in Fig. 7(a), (b). The incident angles are varied in terms of \( \theta \) and \( \phi \) from 0° to 60°. Table 2 represents the lower and upper cutoff frequencies for different incident angle of TE polarized signal on the proposed UWB FSS with reference to \(-10\) dB level. The response of the FSS resembles the characteristics of a band stop filter at 8 GHz with a bandwidth of 5.2 GHz at an attenuation level of 20 dB.

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| Incidence angle (Deg) | Lower cut off frequency at \(-10\) dB (GHz) | Upper cut off frequency at \(-10\) dB (GHz) |
|-----------------------|--------------------------------------------|--------------------------------------------|
| 0                     | 2.39                                       | 13.67                                      |
| 15                    | 2.368                                      | 13.312                                     |
| 30                    | 2.56                                       | 13.08                                      |
| 45                    | 2.88                                       | 12.28                                      |
| 50                    | 3.4                                        | 12.24                                      |
| 60                    | 4.23                                       | 12.256                                     |
Results of Fig. 7 and Tab. 2 easily justify that the designed FSS is stable for different angular variations of incident signal. The FSS reflection response is stable for $\theta$ and $\phi$ variations indicating TE and TM mode of polarization. The $S$ parameters exhibit a similar response for TE and TM mode due to the symmetrical design of FSS structure. This enables the polarization independent operation of the FSS design within the operational band. The start and stop frequencies of the transmission curve with –10 dB reference are 2.39 GHz and 13.67 GHz covering the ultra-wideband range and achieve 141% bandwidth with respect to center frequency of 8 GHz. To the best of authors’ knowledge, the proposed UWB FSS has the highest % bandwidth with polarization and incident angle stability compared to the existing similar works.

The proposed UWB FSS is also compared with same size full metal patch printed on dielectric forming capacitive grids. The reflection magnitude and phase show similar response. Though the transmission response of full metal has an upper cutoff frequency of 15.536 GHz, the proposed FSS show smooth symmetrical response with respect to the center frequency as shown in Fig. 8.

The UWB FSS is fabricated using printing technology. The fabricated FSS prototype consists of $15 \times 15$ unit cells with lateral dimension of $28 \times 28$ cm$^2$ as in Fig. 9. The performance of the UWB FSS is tested by placing it in between two horn antennas separated by a distance of one meter apart of FSS in a partial anechoic chamber as depicted in Fig. 10. The standardized horn antenna used for measuring are, JR-12 double-ridged horn antenna and KU5086 horn antenna respectively from Verdant Telemetry from Vidhyut Yantra Udyog. The measured results of FSS are plotted with frequency ranging between 0–12 GHz due to the limitations in testing facility. The measured transmission response of fabricated FSS for incident angles at $0^\circ$, $15^\circ$, $45^\circ$, and $60^\circ$ are plotted in Fig. 11. The measured plots show bandstop response from 1.66 GHz at normal incidence. For all oblique incidence the transmission response is well below the reference level of –10 dB.
for performance enhancement and for compact wireless FSS is stable up to 60° incident angle with dual polarized band response of 11.3 GHz with 141% bandwidth. The dated. At normal incidence the UWB FSS offers a stop is designed and the performance is experimentally validated during testing. Performance comparisons of designed FSS are tabulated in Tab. 3. The performance of the proposed single layer FSS is better when compared to the earlier designs in the literature with maximum bandwidth and stability.

5. Conclusion

A novel low-profile single layer ultra-wideband FSS is designed and the performance is experimentally validated. At normal incidence the UWB FSS offers a stop band response of 11.3 GHz with 141% bandwidth. The FSS is stable up to 60° incident angle with dual polarization. The proposed UWB-FSS can be utilized in antennas for performance enhancement and for compact wireless devices for electromagnetic shielding in stealth technology.

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