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A Dual Polarized Super-Wideband Frequency Selective Surface with Equivalent Circuit Model

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Abstract

A new single layered Frequency Selective Surface (FSS) with very simple unit cell geometry is proposed in this work. The FSS unit cell is composed of square patch with symmetric square slots in a 4×4 array to cover the super wideband (SWB) from 3.1 GHz to 34.78 GHz (11.22:1) that equivalents fractional bandwidth of 167.26%. The unit cell dimension of the FSS is $0.165\lambda_L \times 0.165\lambda_L$ only where λ_L means the lower cut off frequency of FSS spectrum. The proposed FSS is having bandwidth to dimension ratio 6143.62 and offers similar responses in both the TE & TM modes of polarization. The working band of proposed FSS covers commercial ultra-wideband, WiMAX, ISM bands, WLAN bands, S-C-X-Ku-Ka bands, and 5G NR bands which makes it useful for many present and futuristic wireless communication technologies.

1. Introduction

Frequency selective surface (FSS) is popular periodic surface that is usually fabricated on dielectric substrate to act as reflector/absorber/shielding material [1]. Design of wideband FSS to explore the present and futuristic wireless communication bands becomes very popular among researchers in recent years. S. Patil et al. demonstrated simple FSS that had patch type unit cell of size 35×35 mm^2 and worked in the 3.1–6 GHz band [2]. Bi-layered UWB FSS of unit cell dimension 10.8×10.8 mm^2 was proposed in [3, 4] to provide antenna gain augmentation in the 3.1–10.6 GHz commercial UWB. R. A. Abdulhasan et al. reported single layered UWB FSS that offered 2.6–11.1 GHz bandwidth with unit cell of size 11×11 mm^2 [5]. R. Mondal et. al. reported a UWB FSS with patch type unit cell of size 10×10 mm^2 that worked in the 2.8–12.2 GHz bandwidth [6]. S. Adibi et al. documented a uni layered FSS without uniformity (maximum unit cell size was 9.7×9.7 mm^2 and the smallest unit cell size was 3.35×3.35 mm^2) that offered 2–10.3 GHz bandwidth [7]. S. Xu et al. proposed a three layered FSS to offer -3dB passband of 1.17–7.08 GHz and a -10dB stopband of 7.34–5 GHz [8]. K. Katoch et al. proposed very compact single layered UWB FSS of unit cell size 6×6 mm^2 that worked in the 3–11 GHz band [9]. G. Sen et al. proposed dual band polarization insensitive FSR of unit cell dimension 15×15 mm^2 and offered absorptivity of 2.2–9 GHz [10].

All these recently proposed FSS covers wideband where the upper band edge is limited to maximum of 12 GHz. However, for many present and futuristic wireless communication applications it is evident to realize broader spectrum for getting extensive throughput to match the specification of 5G and beyond wireless technologies. Considering this aspect, a compact single layered SWB FSS is designed and evaluated in this work. The next section describes the FSS geometry. Section 3 includes FSS characteristic analysis. Conclusion and comparative analysis are reported in section 4.

2. Design of FSS

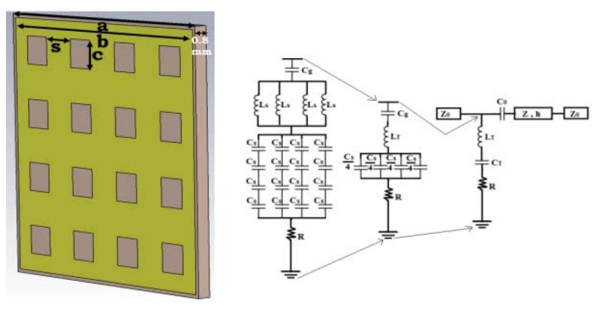
An uni-planar frequency selective surface with unit cell shape of square patch is printed on top of affordable FR-4 dielectric substrate. 4×4 array of square slots is incorporated inside the square patch to make the surface current more effective thus to enhance the overall working bandwidth. The schematic of FSS unit cell with design parameters is shown in figure 1 which is analyzed using CST simulator. Intended to realize the super wide FSS bandwidth, the following design equations are considered for initiation of unit cell design,

$$a \approx \frac{\lambda_L}{6} \qquad (1)$$

$$b \approx a - h \qquad (2)$$

$$(c + s) \approx \frac{\lambda_L}{25} \qquad (3)$$

Here a, b, c and s represent the design parameters as shown in figure 1(a), h represents substrate thickness and λ_L represents the lower cut off frequency of commercial UWB. Parametric studies are considered to finalize the optimal values of design parameters. As shown in figure 2, the parametric study of transmission/reflection coefficients (S_{21}/S_{11}) for three different values of FSS unit cell outer size (a) are considered.



(a) (b)

Figure 1. (a) Schematic of FSS unit cell with design parameters (b) Equivalent circuit model of FSS

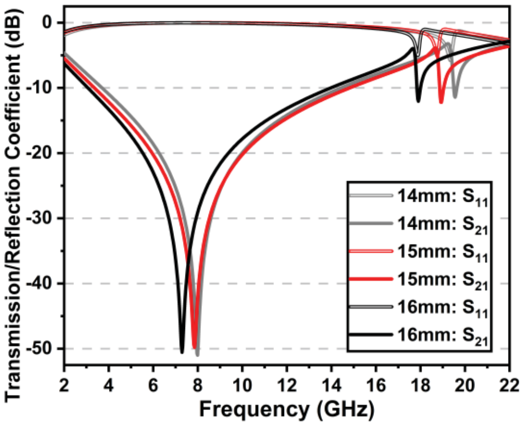


Figure 2. Transmission (S_{21}) and reflection (S_{11}) coefficients of FSS for three different values of unit cell outer dimension (a).

For FSS size of a=16mm the lower band edge is at 3.1GHz which is the desired value. However, for other two 'a' value i.e. 14mm & 15mm, the FSS lower band is shifted towards higher frequency side. Therefore a=16mm is chosen as optimal value.

Now, to enhance the FSS bandwidth (S_{21}<-10 dB & S_{11}~0 dB) by extending the upper band edge, it is vital to enhance the gap between neighbor square slots that affects on capacitance value as shown in the ECM. Parametric study as plotted in figure 3 is exhibited to identify the optimal values of square slot size (c) and the gap (s) between the slots. The bandwidth is enhanced with increasing the gap between the slots. However, beyond s=2.16mm, the FSS band becomes restricted. Therefore, the optimal values of (c, s) are chosen is (1.75mm, 2.16mm) which covers the highest spectrum of 3.1–34.78GHz. The final values of FSS unit cell design parameters are a=16mm, b=15.64mm, c=1.75mm and s=2.16mm. The FSS is fabricated on FR-4 substrate that has permittivity 4.4, loss tangent 0.018 and thickness 0.8mm.

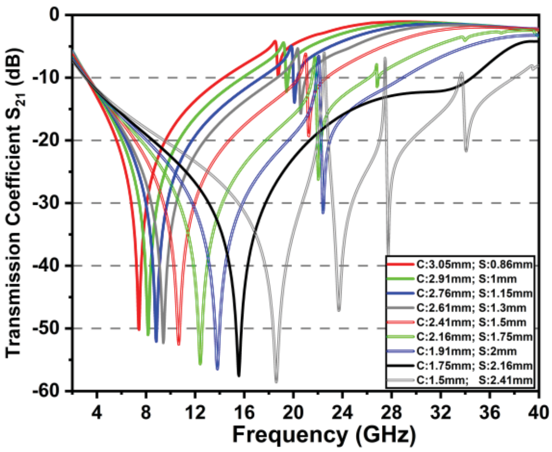


Figure 3. Transmission (S_{21}) and reflection (S_{11}) coefficients of FSS for different values of s & c.

3. ECM of FSS

The equivalent circuit model (ECM) of proposed FSS is presented in Figure 1(b). The design process exhibits a traditional square loop lengthwise the outlying of component cell which can also be thought as LC resonator. L_s is due to the copper ring and C_g is because of the gap among neighbor small cells of FSS.

$$C_g \approx \varepsilon_0 \varepsilon_r \left(\frac{a \times l}{g}\right) \quad (4)$$

Here l is depth of copper, ε_0=8.85×10^{-12} F/m and ε_r is relative permittivity of FR-4 that is 4.4 and g is the spacing between two neighbor FSS cells. Moreover, a 4×4 array of square slots is embedded in square patch. C_s realized inside slots and L_s created inside strips. The inductance is realized through the square metal strips. It can be identified using,

$$L_s \approx 2a\left[\log\frac{2a}{s} + \frac{1}{2}\right] (5)$$

C_s obtained among the square loops, differed by slots and maintained by fluctuating c and s as shown in (6),

$$C_s \approx \varepsilon_0 \varepsilon_r l \ (6)$$

Entire inductance (L_T) calculated using,

$$L_T = \frac{L_s}{4} = \frac{a}{2}\left[\log\left(\frac{2a}{s}\right) + \frac{1}{2}\right] (7)$$

Entire capacitance (C_T) calculated using,

$$C_T = \varepsilon_0 \varepsilon_r l \left(\frac{a}{a+g}\right) (8)$$

Finally, the resonance frequency (f_n) calculated using,

$$f_n = \frac{1}{2\pi\sqrt{L_T C_T}} \quad (9)$$

4. Characteristic Analysis of FSS

The characteristic analysis of the proposed FSS is presented in this section by incorporating the transmission/reflection coefficient plots in both TE and TM planes of polarization and simulated surface current plot of FSS unit cell in various frequency points in the entire FSS bandwidth.

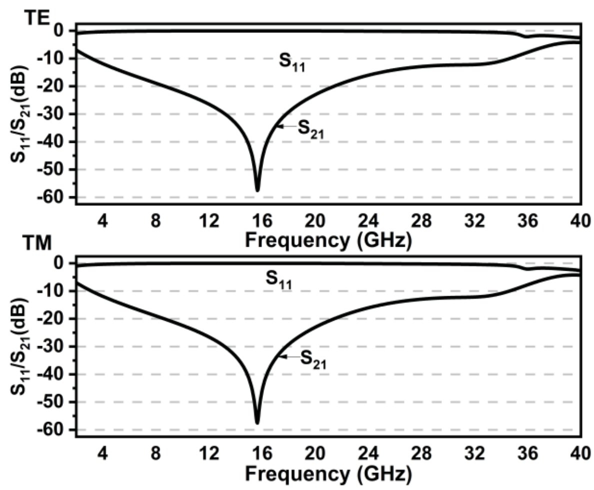


Figure 4. Transmission (S_{21}) and reflection (S_{11}) coefficients of FSS in TE and TM planes of polarization.

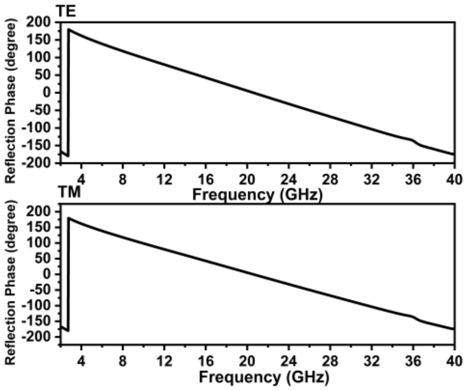


Figure 5. Phase of reflection coefficient (S_{11}) of FSS in TE and TM planes of polarization.

As presented in figure 4, the FSS shows similar S_{21}/S_{11} responses in both the TE and TM polarizations. The FSS bandwidth is from 3.1 to 34.78 GHz where S_{21} is below -10dB and S_{11} is near 0dB. It reflects fractional bandwidth of 167.26% and bandwidth to dimension ratio (BDR) 6143.62. Also, the phase of S_{11} is plotted in figure 5 that depicts a linearly decreasing profile. The linearly decreasing profile is very significant as it ensures the proper reflective nature of FSS. Such FSS can be added with antennas as superstrate or substrate to improve the radiation in the desired direction.

The simulated surface current of FSS unit cell is shown in figure 6. High symmetric current flow in all different frequencies for both the polarizations is realized. The dense current near slot peripherals indicate the increment in effective current path due to the addition of slots and thus improvement of FSS bandwidth.

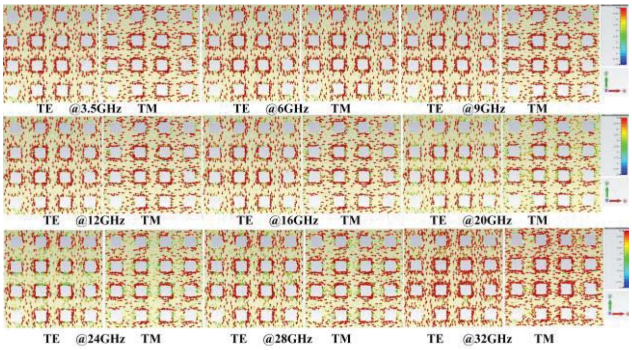


Figure 6. Simulated surface current on FSS unit cell for both TE and TM planes of polarization at different frequencies, covering the entire FSS bandwidth.

5. Conclusions

This work includes the design methodology of a new uniplanar super wideband FSS with analysis based on equivalent circuit model. The FSS unit cell is very simply designed and fabricated on affordable FR-4 substrate. The FSS offers spectrum from 3.1 to 34.78 GHz SWB which makes this FSS very promising candidate for many modern and futuristic wireless technologies. Finally, the proposed work is compared with recently reported wideband FSS in table-1 where it can be seen that the proposed FSS offers highest bandwidth coverage with moderate size.

Table 1: Comparison with similar recent literatures

Ref No./Yr.	Size of Unit Cell (mm^2)	Lay -er	Bandwidth (GHz)
2/2017	$0.36\lambda_L \times 0.36\lambda_L$	1	3.1-6 (63.7%)
3/2018	$0.11\lambda_L \times 0.11\lambda_L$	2	3.1-10.6 (109.5%)
5/2019	$0.11\lambda_L \times 0.11\lambda_L$	1	2.6-11.1 (124.1%)
6/2020	$0.1\lambda_L \times 0.1\lambda_L$	1	2.8-12.2 (125.3%)
7/2021	$0.1\lambda_L \times 0.1\lambda_L$	1	2-10.3 (134.9%)
9/2021	$0.06\lambda_L \times 0.06\lambda_L$	1	3-11 (114.3%)
10/2021	$0.155\lambda_L \times 0.155\lambda_L$	2	2.2-9 (121.4%)
This work	$0.165\lambda_L \times 0.165\lambda_L$	1	3.1-34.78 (167.26%)

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