A 2.5-Dimensional Miniaturized Frequency Selective Surface based on Convoluted Geometry

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Abstract

A miniaturized-element frequency selective surface (FSS) based filter geometry has been designed and analyzed in this paper. The geometry is made of convoluted meander lines printed on both sides of a dielectric and the patterns are joined by metallic vias engraved through the substrate, thereby reducing the operating frequency. This results in a compact 2.5-dimensional filter geometry exhibiting a combination of bandstop and bandpass responses, having unit cell dimensions of $0.044\lambda \times 0.044\lambda$, where λ is the operating wavelength at the lowest operating frequency (1.10 GHz). The proposed topology is four-fold symmetric as well as angularly stable for different polarizations. Parametric variation and other set of analyses have also been carried out to explain the operating principle of the proposed FSS. The proposed FSS design can be considered as a potential candidate for several radome applications.

1. Introduction

Frequency selective surfaces (FSSs) are planar array structures, which can effectively regulate the transmission and reflection responses of incident electromagnetic (EM) waves [1]. By careful design, an FSS structure can exhibit lowpass, highpass, bandpass, and/or bandstop characteristics at different frequencies, thereby behaving as a spatial filter. The geometry is usually made of a dielectric substrate and metallic designs printed on either one side or both sides of the substrate. The dielectric mainly provides the mechanical strength and electrical compactness, whereas the metal arrays produce selective transmittance/ reflectance to the impinging EM wave. Because of its manifold advantages, FSS has a wide variety of applications in filters, couples, polarizers, absorbers, antennas, radomes, shielding, and other aspects [2]-[4].

These FSS structures, during implementation in a limited space, should have compact size and low profile such that a large number of FSS unit cells can be accommodated for mimicking the actual response. This necessitates to design miniaturized unit cell FSSs to reflect the desired response. Further, the appearance of grating lobes gets delayed in miniaturized topologies, and results in higher angular stability [5]. Hence, several miniaturized-unit cell FSSs have recently been developed exploiting different topologies, such as interdigital capacitor, hexagon element, spiral geometry, meander line, etc. [6]-[9]. However, two-dimensional (2-D) FSSs have performance limitations even after implementing different types of convoluted designs. In contrast, a 2.5-D FSS geometry can exhibit an improved miniaturization response by exploiting periodic patterns as well as the dielectric substrate. Metallic vias are generally used in a 2.5-D FSS to connect the bottom and top metallic surfaces, subsequently increasing the electrical length and reducing the resonating frequency. A few 2.5-D FSSs have recently been developed exhibiting compact geometries, but require further refinement [10]-[13].

A 2.5-D based FSS geometry is presented in this paper with a substantial improvement in angular stability as well as miniaturization performance. The proposed design is made of convoluted geometries both in lower and upper layers of a dielectric substrate and are joined through metallic vias. The topology is made such that the frequency response is polarization-insensitive, angularly stable, and exhibits a good miniaturization response. Detailed analyses have also been carried out in the subsequent sections.

2. Design and Analysis

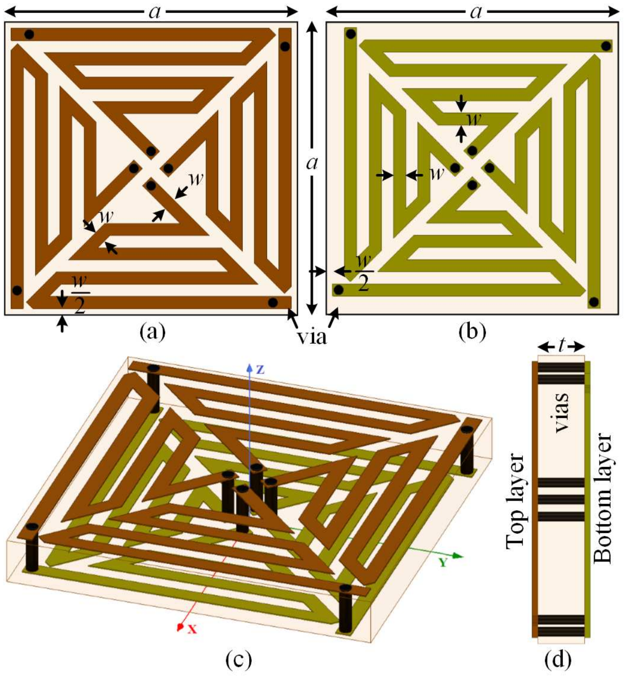


Figure 1. 2.5-D FSS unit cell geometry. (a) Top layer. (b) Bottom layer. (c) Isometric view of the complete geometry. (d) Side view of the structure. The geometric dimensions are: $w = 0.5$ mm, $a = 12$ mm, and $t = 1.6$ mm.

The proposed 2.5-D FSS unit cell geometry is depicted in Fig. 1. The top surface consists of a convoluted meander pattern, whereas the bottom surface is made of the similar topology orthogonally rotated. The top and bottom metal patterns are printed on different sides of a dielectric, and are connected through eight set of metallic vias engraved through the substrate. The dielectric used in the structure is FR4 ($\varepsilon_r = 4.4$ and *tan* $\delta = 0.02$), whereas the top and bottom metallic patterns are made of copper material. The substrate height is chosen as 1.6 mm, whereas the metallic vias have a radius of 0.2 mm. The other dimensions are illustrated in Fig. 1.

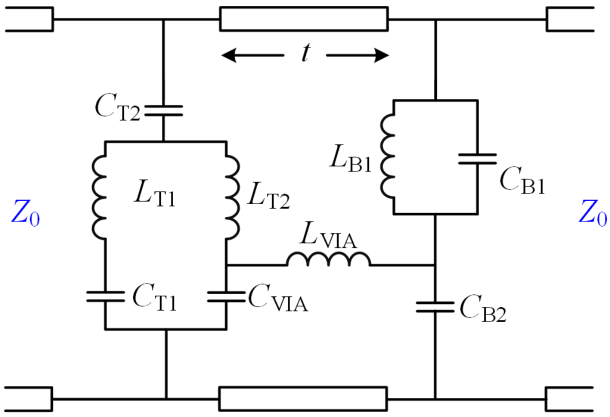


Figure 2. Equivalent circuit of the proposed FSS structure.

While analyzing the circuit diagram of the proposed geometry, the top as well as bottom metallic patterns realize a series-parallel combination of capacitance and inductance. The sections parallel to the electric field direction will exhibit distributed circuit components, while the sections perpendicular to the electric field will not display any significant effect. Fig. 2 shows the circuit model of the proposed structure, where in addition to the top and bottom circuit elements, a set of via inductance (L_{VIA}) and capacitance (C_{VIA}) are added, owing to the metallic vias in the geometry. This via inductance reduces the transmission line section effect significantly, whereas the via capacitance assists in generating a combination of bandpass-bandstop filter response.

While doing full-wave simulation for the proposed FSS geometry, two low frequency responses are obtained from the geometry, one bandstop response at 1.10 GHz and one bandpass response at 1.46 GHz, as shown in Fig. 3. The bandstop response exhibits a reflection loss of 0.54 dB (and insertion loss of 24.44 dB), whereas the bandpass behavior has a small insertion loss of 0.42 dB (and reflection loss of 23.88 dB). A set of higher-order resonance is also observed at 2.78 GHz and 2.82 GHz, corresponding to the bandstop and bandpass responses, respectively.

The surface current distributions of the proposed 2.5-D FSS are depicted for two different frequencies, viz. 1.10 GHz and 1.46 GHz in Figs. 4(a) and 4(b), respectively. For both the frequencies, the current is mainly concentrated in the meander lines parallel to the electric field only. Those meander lines provide the requisite inductance and their consecutive gaps deliver the capacitance for resulting in the resonance frequencies. It is also observed that the surface current flows between the top and bottom metallic surfaces through the metallic vias, and thus increase the overall electrical path for generating low frequency responses.

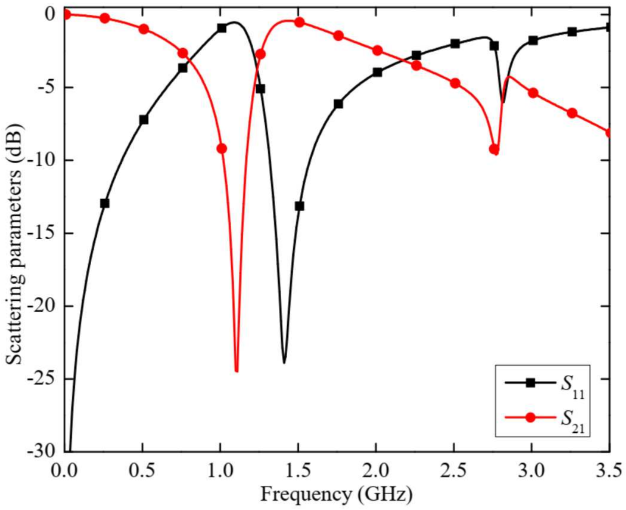


Figure 3. Simulated reflection coefficient (S_{11}) and transmission coefficient (S_{21}) of the proposed FSS.

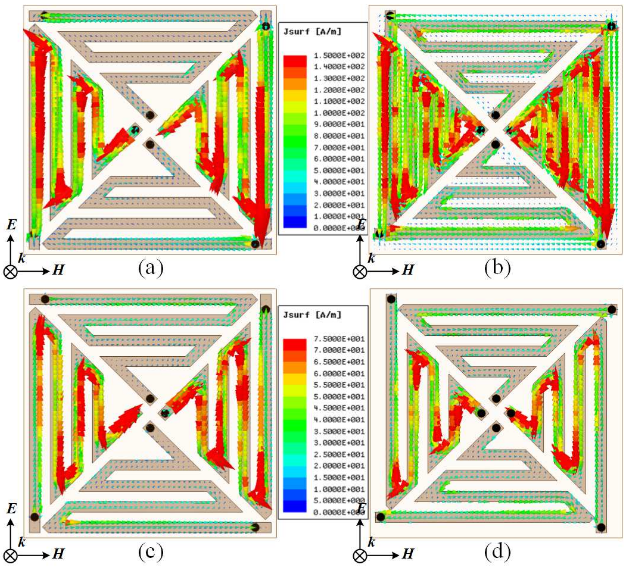


Figure 4. Surface current distributions at 1.10 GHz: (a) top layer, (b) bottom layer, and 1.46 GHz: (c) top layer, (d) bottom layer.

To validate the metallic via contribution, the proposed FSS is studied with and without the presence of metallic vias in Fig. 5. The current is separately flowing through the top and bottom metallic surfaces in absence of the vias, as no closed loop has been formed [14]. The via inductance and capacitance are thus no longer present, resulting in a higher frequency response.

The contribution of a few geometric parameters have also been studied in this paper. When the meander line width (*w*) is varied while keeping all other dimensions constant, the unit cell size as well as the operating frequency are modified accordingly, as shown in Fig. 6. However, the electrical size of the geometry remains almost constant, due to concurrent shift in the unit cell size and the resonance frequency [15]. Other dimensions, such as substrate thickness, number of meaner fingers, etc. are also varied and their responses are studied to optimize the FSS design.

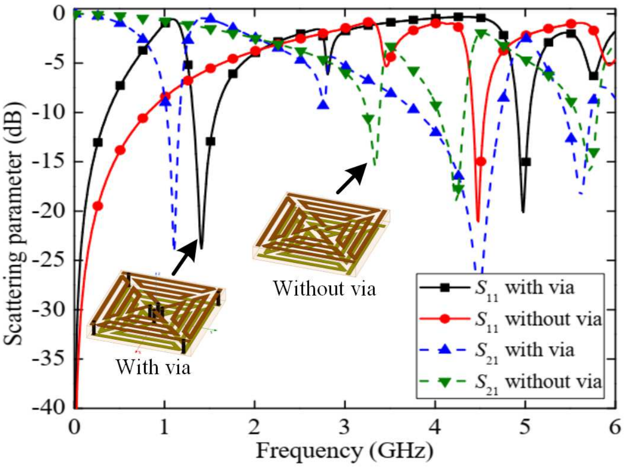


Figure 5. Comparison of scattering parameters of the proposed 2.5-D FSS, without and with metallic vias.

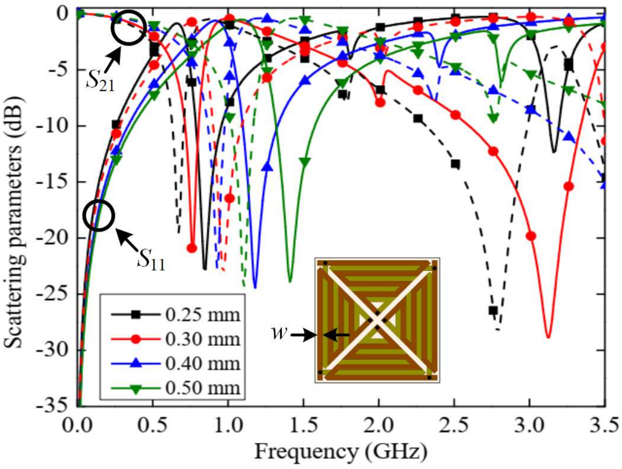


Figure 6. Simulated frequency response of the 2.5-D FSS while varying the meander line width (*w*) value.

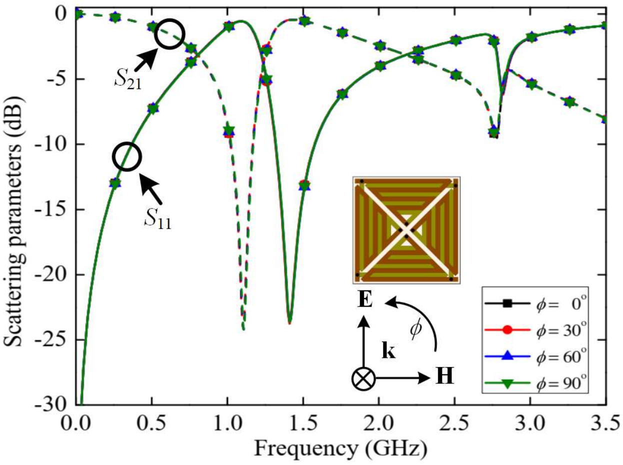
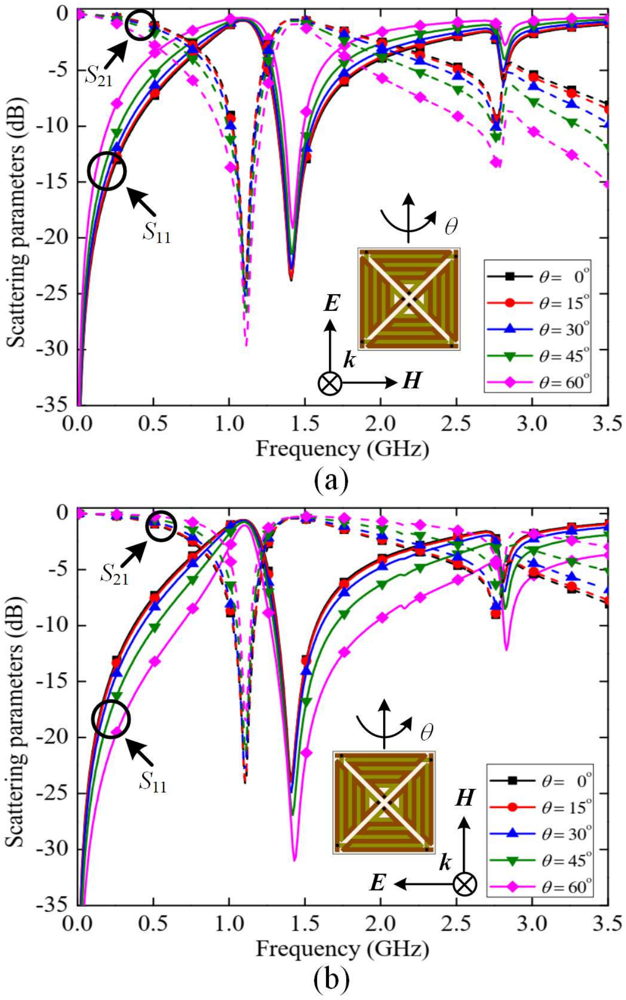


Figure 7. Simulated frequency response of the 2.5-D FSS for different angles of polarization (ϕ).

The design, while studied under different polarization angles (ϕ), is found to display identical frequency responses for all the polarization angles, as shown in Fig. 7. It further confirms that the topology is polarization-insensitive. The geometry has also been scrutinized for different incident angles (θ) and depicted in Fig. 8. It is observed that both the modes offer angularly stable responses above 60° angles of incidence. Although the resonant frequencies remain almost same for higher incident angles, the operating bandwidth changes in opposite ways due to the difference in impedance condition under oblique incidence for TE and TM modes.



(a)

(b)

Figure 8. Simulated frequency response of the 2.5-D FSS under (a) transverse electric (TE), and (b) transverse magnetic (TM) modes. θ indicates the angle of incidence.

3. Conclusion

A miniaturized FSS geometry has been presented in this paper exploiting the convoluted meander geometry. The topology is designed on 2.5-D concept by forming closed loops through joining the bottom and top metallic patterns with plated-through-hole vias. This results in a compact unit cell size as well as higher angular stability. The design, while compared with earlier reported compact FSS structures in Table 1, shows an improved performance in terms of miniaturization characteristic. Other sets of analyses have also been carried out to investigate the operational principle of the proposed FSS and demonstrate its potential for various spatial filter applications.

Table 1: Comparison with Existing Miniaturized FSSs

FSS structure	Resonant frequency (GHz)	Dielectric constant (ε_r)	Unit cell size (mm)	Unit cell size (λ_o)	Angular stability
[8]	3.33	2.2	6.3	0.067	80°
[9]	2.35	4.4	8.4	0.065	60°
[10]	2.85	4.4	5	0.048	60°
[11]	1.89	4.4	10	0.063	45°
[12]	0.9	2.2	24	0.072	60°
[13]	1.60	4.4	10	0.053	60°
Proposed FSS	**1.10**	**4.4**	**12**	**0.044**	**60°**

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