Dual Layer Convoluted Frequency Selective Surface Design in the 2.4 GHz and 5.8 GHz ISM Bands

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Abstract ─ Indoor wireless devices operating in 2.4 GHz and 5.8 GHz ISM bands have a wide range of usage area. However, mutual interference in neighboring networks degrades the system performance. It can also cause significant problems in secure personal communications on such wireless networks. Covering building walls with a band stop frequency selective surface (FSS) can be an efficient solution for such problems. Many available FSS structures are designed to have a single stop band. They are also subject to narrow incidence angle range and sensitive to the polarization of the wave. On the other hand, in some studies, FSSs with double stop band are designed such that the second stop band is to be the harmonic frequency of the first band. In this study, a dual layer frequency selective surface element geometry is introduced. This geometry is capable of at least 20 dB attenuation of incoming signals within the incident angle range from 0 to 60 degrees and for all polarizations. Another important contribution is that a periodic cell size of approximately one-tenth of the wavelength corresponding to 2.4 GHz is obtained. Besides, a new design methodology that enables almost independent optimization of each layer at its resonance frequency is also introduced.

Index Terms ─ Frequency selective surface, FSS, indoor propagation, interference, periodic structures, wireless communication, Wireless Local Area Network (WLAN).

I. INTRODUCTION

The utilization of wireless networks within buildings in ISM (The industrial, Scientific and Medical) frequency bands has been grown rapidly in recent years. But, the resulting mutual interferences among the adjacent networks degrades the system performances. Another important problem is the security risks of personal communication on such wireless networks. Some advanced signal processing methods, specific antenna designs and encryption techniques have been recommended to solve these problems in [1, 2]. An efficient solution for interference and security risks encountered within the wireless networks is to affix a frequency selective surface (FSS) onto subsisting prevalent construction materials considering the filtering properties of FSSs at desired resonance frequencies [3, 4, 5, 6, 7, 8].

Periodic conducting structures, known as frequency selective surfaces, have filter characteristics depending upon their geometries when interacting with electromagnetic waves [9]. They have been utilized in many applications and systems such as antennas, radomes, wireless local area networks (WLAN) [9].

The isolation capabilities of band stop FSSs have been investigated by different researchers for WLAN security and interference mitigation in indoor environments [4, 5, 6, 7]. According to the given results, FSSs are capable of providing minimum 10 dB isolation between two adjacent rooms in ISM bands [6]. These researches also showed that wireless signals in an indoor environment have a wide range of incidence angles. Although 2.45 GHz and 5.8 GHz ISM bands have been investigated individually for FSS designs, there is a gap in the literature for double band design, which stops both ISM bands within a single FSS structure [10].

In this study, 20 dB attenuation on the transmission (S_{21}) parameter is desired for ISM bands of interest while providing maximum transmission in other frequency bands for a wide range of oblique incidence angles and for all polarizations. To this end, two different convoluted FSS geometries are designed in a dual layer structure. Such a structure can attain frequency stability for oblique incidence angles and shifts grating lobes to higher frequencies. Multiple layer FSS structures are also considered to achieve maximum attenuation levels for all ISM frequency bands. However, mutual effect between each layer is an important problem for the optimization process of multi-layer structures. Inspection of the transmission curves clearly shows that cascaded periodic structures (double layer), compared to a single layer structure, have almost same frequency characteristic with an observing shift at the resonance frequency [9]. Therefore, identical geometries on each layer is considered to optimize each layer independently.

Equivalent circuit (EC) model is applied to

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understand the influence of geometrical parameters of the FSS geometries on their frequency responses. EC model and a finite element method solver for electromagnetic structures (Ansoft HFSS v.15 software) are performed together to analyze and optimize the proposed FSS structure rapidly. HFSS simulates a unit cell in an infinite periodic structure by using periodic boundaries with Floquet ports. When a Floquet port is defined, a set of modes known as Floquet modes represent the fields on the port boundary. The Floquet modes are plane waves with propagation direction set by the frequency, phasing and geometry of the periodic structure.

The periodic cell size of $0.1\lambda_{2.4GHz}$ is achieved by meandering the conducting geometries of FSS. Besides having 90% of miniaturizing, proposed FSS element geometry has frequency stability at all polarizations with a minimum 20 dB of attenuation for incident angles varies from 0^0 to 60^0.

The paper is organized as follows: Section II explains FSS theory and FSS analysis methods. Multilayer FSS design process, simulation and measurement results are presented in Section III, and the results are discussed in Section IV.

II. FSS THEORY

Frequency selective surfaces are periodic structures that filter certain frequency bands depending on their geometries during interaction with electromagnetic waves. Numerical methods are mostly employed to analyze the frequency characteristics of FSS geometries [11, 12]. Despite their accuracy in analysis, these techniques do not provide information into the physics behind the structures. On the contrary, EC models are helpful for determining the effect of the geometrical parameters on the frequency characteristics of the FSSs [13]. FSS geometry can be represented in the EC model by a single series LC circuit shunted to a transmission line of free space characteristic impedance (Z_o), which is seen in Fig. 1. The width of the gap (s) and the gap (g) between periodic element geometries primarily determine the equivalent capacitance ($C \propto \frac{s}{g}$). The length (d) and the width (w) of the current path primarily determine the equivalent inductance ($L \propto \frac{d}{w}$) of periodic element geometries.

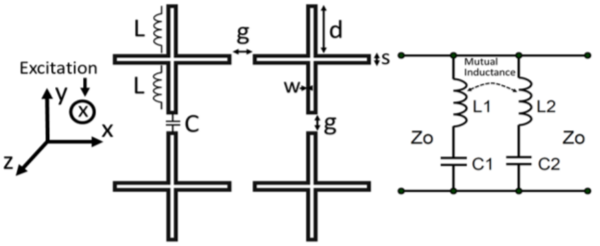


Fig. 1. FSS and its equivalent circuit.

Equivalent impedance (Z) and the resonance frequency (f_0) of such an FSS structure are derived from the EC model described here and can be expressed as in Eq. (1). It can be concluded that the impedance of FSS has one zero at a certain frequency and therefore, the wave is unable to transmit through the surface at that frequency:

$$Z = jwL + \frac{1}{jwC} = j\left(wL - \frac{1}{wC}\right),\ f_0 = \frac{1}{2\pi\sqrt{LC}}. \qquad (1)$$

From the expressions in Eq.1 and EC model in Fig. 1, it is obvious that the relationship between the geometrical parameters and the frequency characteristic of the FSS can be determined by using the EC model. Therefore, EC models and numerical analysis techniques can also be performed together to achieve the desired frequency characteristics rapidly [14]. It is important that the periodic cell size should be smaller enough than the resonance wavelength to reduce the sensitivity of the first resonant frequency to the angle of incident wave [9]. Obtaining smaller cell sizes is generally achieved by increasing the effective electrical length of the metallic patch [15]. This method is done either by using lumped elements in every cell of the FSS or meandering the excited metal patch. Using lumped elements in every FSS cell is an effective way to reduce unit cell sizes. However, their costs are high and their electrical properties depend on temperature, moisture etc. Therefore, meandering of the conducting paths of FSS geometries is considered to reduce unit cell size in this study as in [16].

Several methods are defined in the literature in order to achieve multiple stop band FSS behavior [17]. Hybrid geometries are used in one unit cell to achieve multiple stop band behavior [9]. In this method, the distance between the same resonant parts of the two adjacent unit cells cannot be shortened sufficiently in order to have a good frequency stability. As another method, multi-layer FSS structures are used to achieve multiple stop bands. In this study, two different convoluted FSS geometries are used in a dual layer structure to achieve frequency stability for oblique incidence angles. However, an important problem in the optimization process is the undesirable consequences of the mutual effect between each layer. Fortunately, using similar unit cell geometries in each layer enables us to optimize each layer independently and consequently, this approach is proposed in this paper to overcome such mutual effect problems.

III. DESIGN & MEASUREMENT

A band stop FSS design with a good attenuation performance in both 2.45 GHz and 5.8 GHz ISM bands for oblique incidence angles ranging from 0 to 60 degrees is aimed in this study. In order to achieve maximum attenuation and stable frequency characteristics, a novel dual layer convoluted FSS structure is considered. An EC model of a general dual layer FSS structure having different periodic element geometries on each layer is shown in Fig. 2. Each layer of the structure acts as a reflector for the desired WLAN frequency bands and can be modeled by a serial LC circuit. The coupling effect between two layers of the FSS is represented by a mutual inductance. Similar to the basic structure described in Section 2, the capacitance and inductance values of the equivalent LC circuits of the dual layer structure can be determined by using the periodic element geometries of each layer for the desired resonance frequencies.

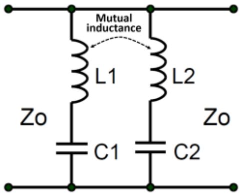


Fig. 2. EC model of a dual layer FSS structure.

Equivalent impedance of the dual layer FSS can be derived from the circuit model given in Fig. 2 as:

$$Z=\frac{(1-w^2L_1'C_1)(1-w^2L_2'C_2)}{\mathrm{jw}(C_1+C_2-w^2C_1C_2(L_1'+L_2'))} \qquad (2)$$

$$L_1'=L_1-M,\ L_2'=L_2+M.$$

It is obvious that FSS behaves as a metal wall when the impedance Z approaches to zero and as a result, the resonance frequencies of the FSS are derived as:

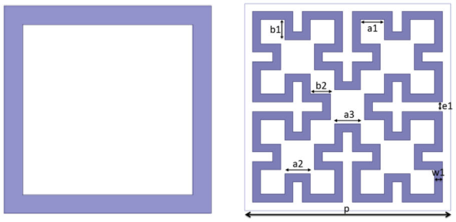
$$f_{2.45GHz}=\frac{1}{2\pi\sqrt{L_1'C_1}},f_{5.8GHz}=\frac{1}{2\pi\sqrt{L_2'C_2}}. \qquad (3)$$

As mentioned in Section 2, the desired frequency response can be obtained by changing the element dimensions of the periodic structure considering the relationships between the equivalent capacitance and inductance values and element geometry. It is well known that frequency characteristic of a single layer FSS is the same with a multilayer FSS structure having the same FSS geometries on each layer [10]. Therefore, using identical geometries on each layer allows us to reduce the mutual effect between the layers and thus to optimize each layer individually.

In the first design stage, “Square Loop” element (Fig. 3 (a)) geometry, which is suitable for meandering, is selected. The optimization process starts with the initial selection of the FSS geometry’s dimensions in accordance with the desired resonance frequency. However, since the additive higher frequency stop band (5.8 GHz) mostly pushes the first stop band to lower frequencies [9], this geometry is convoluted and optimized to achieve a stop band with a slightly higher frequency than the lowest (first) ISM band (2.4 GHz). The analysis for the observed frequency shifts in the frequency response obtained from HFSS simulations is done. Then, these analysis results are used to predict new dimensions of the FSS elements according to relationships given in Section 2: $(C\propto\frac{s}{g}, L\propto\frac{d}{w})$. Subsequently, these new dimensions are optimized by using parametric analysis feature of HFSS software. Thus, the optimization process is shortened by utilizing EC model.

EC model is only valid for the fundamental Floquet modes. In this work, only fundamental modes propagate in the intended frequency band due to having miniaturized structure. However, HFSS simulations are executed for 10 Floquet modes, due to the proposed work is double-layered.

Dimensions and the layout of the proposed FSS geometry are depicted in Fig. 3 (b). At the end of the optimization process, the following dimensions are obtained: h=1.6 mm (thickness of the FR4 substrate), g=1.06674 mm (gap between the periodic elements), w1=0.5288, p=13.5474, b1=1.3221, b2=1.3221, e=0.6346, a1=1.5865, a2=1.6923 and a3=1.6923.



(a) (b)

Fig. 3. FSS geometries: (a) “Square Loop” and (b) “Convoluted Square Loop”.

Figure 4 shows the obtained results at incidence angle of 45^0 for both TE and TM polarizations, respectively. According to the obtained results, minimum 20 dB attenuation is achieved at 2.4 GHz ISM band for oblique incidence angles from normal to 60^0 for all polarizations.

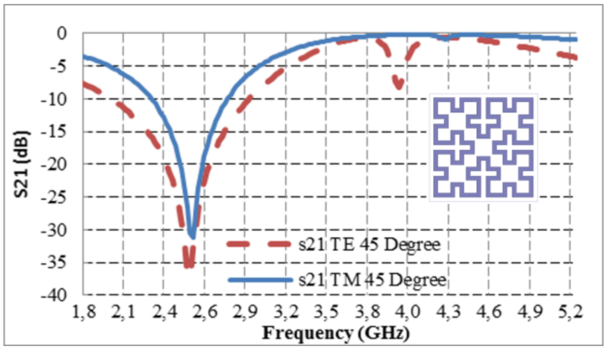


Fig. 4. S_{21} frequency curves for “Convoluted Square Loop” geometry, TE and TM polarization ($\theta=45^0$).

In the second stage of the double layer FSS design, in order to observe the coupling effect between the layers, “Convoluted Square Loop” periodic element geometry (Fig. 5) is used on each layer of the FSS with the same parameter values.

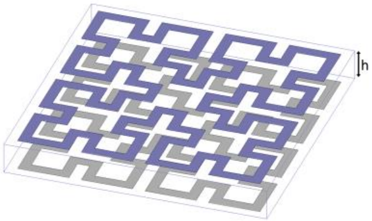


Fig. 5. Double layer periodic element structure.

Simulations are performed by HFSS software. Same frequency behavior (Fig. 6) is obtained with a shift in the resonance frequency as expected [8]. A slight increase over the bandwidth is also observed for the dual layer FSS.

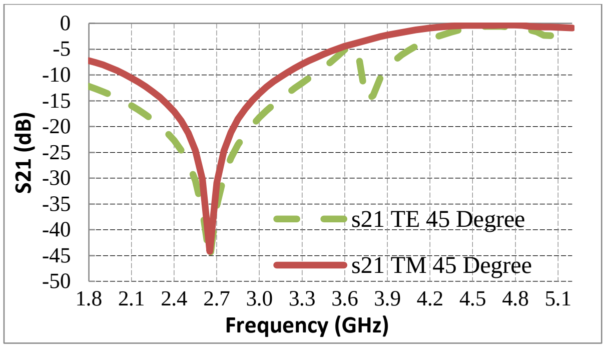
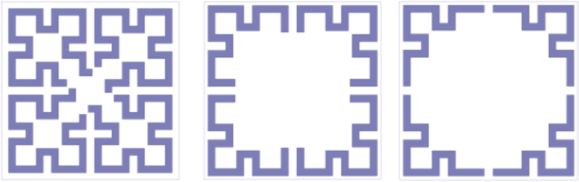


Fig. 6. S$_{21}$ frequency curves for dual layer "Convoluted Square" geometry for TE and TM polarization ($\theta=45^0$).

According to EC model, the resonance frequency of the FSS is inversely proportional to the equivalent inductance values ($L\propto\frac{d}{w}$) which are mainly determined by the length and the width of the current path of the FSS. In order to obtain the second resonance frequency at 5.8 GHz, effective electrical length of the conducting patch is shortened on the top layer as shown in Fig. 7 with different design phases.



(a) Phase 1 (b) Phase 2 (c) Phase 3

Fig. 7. Design phases of the FSS geometry on the top layer.

Obtained results show that the use of identical geometries on each layer enables us to optimize the resonance frequencies independently (Fig. 8). It is observed that any change of the effective current path length on the top layer has a minor effect on the resonance frequency of the bottom layer (2.45 GHz). On the other hand, effective electrical length of the conducting patch on the top layer affects the second resonance frequency (5.8 GHz) directly.

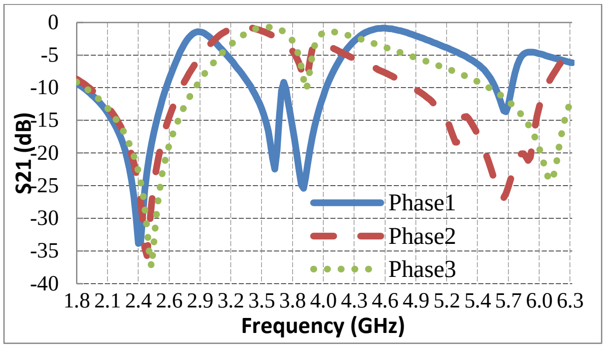
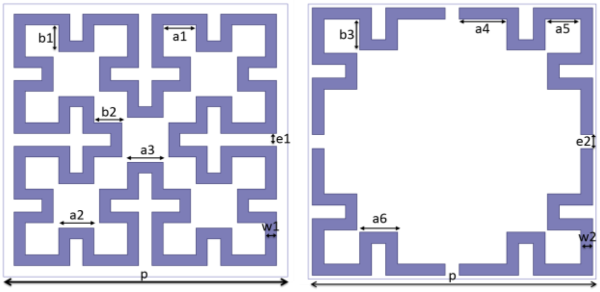


Fig. 8. S$_{21}$ frequency curves for TE polarization for $\theta=45^0$ (Phase 1, Phase 2, Phase 3).

As a result, "Phase 3" FSS geometry is selected as the final geometry of the top layer in the last design stage. In order to shift the second resonance frequency to 5.8 GHz and to narrow its bandwidth, top layer geometry is slightly scaled up. The dimensions and the layout of the final FSS structure are depicted in Fig. 9. The thickness (h) of the FR4 substrate (relative dielectric permittivity 4.54, loss tangent 0.027) is 1.6 mm, the gaps between the periodic elements are 0.36 mm (g1), 0.48 (g2) for the top and bottom layers, respectively. The other parameter values (in mm) are w1=0.52, w2=0.56, p=13.54, b1=1.32, b2=1.32, b3=1.55, e1=0.63, e2=0.67, a1=1.58, a2=1.69, a3=1.69, a4=2.23, a5=1.67 and a6=1.78. According to the obtained simulation results (Figs. 10-11), at least 20 dB attenuation is achieved at oblique incidence angles from normal to 60^0 for all polarizations. A periodic cell size (p=13.54 mm) which is less than one-tenth of the first resonance wavelength is obtained in the design which leads frequency stability within a wide range of incidence angles.



(a) Bottom layer (b) Top layer

Fig. 9. "Updated Phase 3" dual layer FSS geometry.

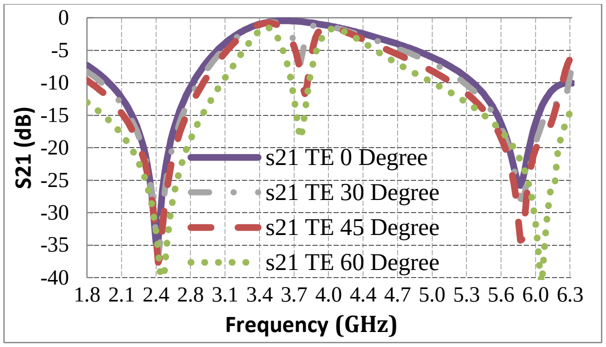


Fig. 10. S_{21} frequency curves for “Updated Phase 3” dual layer FSS geometry for TE polarization ($\theta=0^0$, $\theta=30^0$, $\theta=45^0$, $\theta=60^0$).

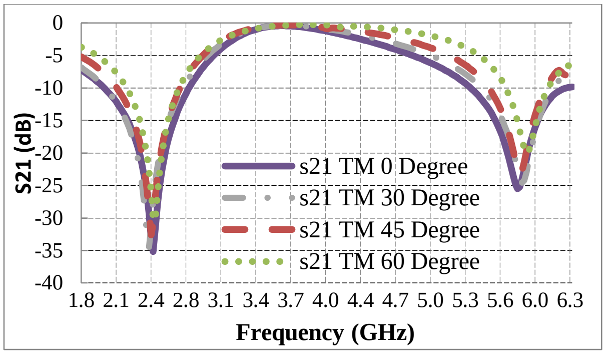


Fig. 11. S_{21} frequency curves for “Updated Phase 3” dual layer geometry for TM polarization ($\theta=0^0$, $\theta=30^0$, $\theta=45^0$, $\theta=60^0$).

As shown in Figs. 12 and 13, the measured results of the manufactured prototype satisfy at least 20 dB attenuation for the desired frequency bands and there is a good agreement between measurement and simulation results.

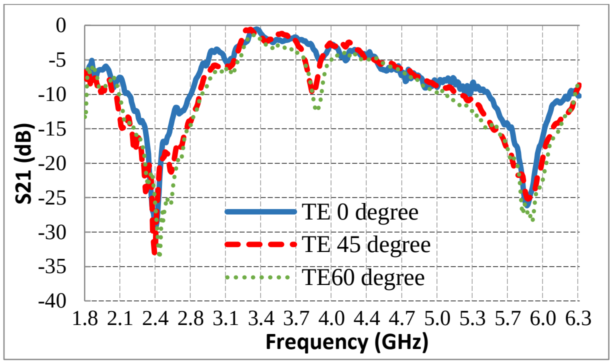


Fig. 12. Measured S_{21} frequency curves for TE polarization ($\theta=0^0$, $\theta=45^0$, $\theta=60^0$).

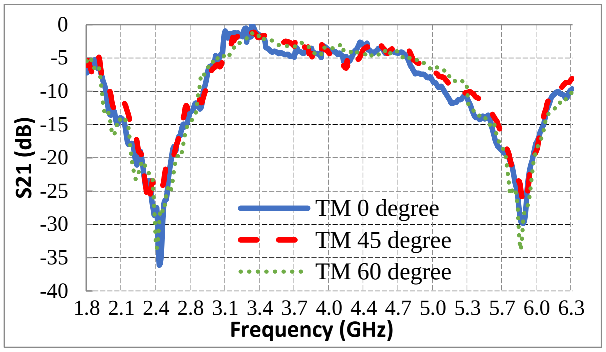


Fig. 13. Measured S_{21} frequency curves for TM polarization ($\theta=0^0$, $\theta=45^0$, $\theta=60^0$).

IV. CONCLUSION

A new dual layer band stop FSS structure is designed for mitigating both interference and WLAN security risks within the buildings in the unlicensed 2.4 GHz and 5.4 GHz ISM bands. The new element geometry is capable of achieving a stable frequency response for a wide range of oblique incidence angles. This is due to a periodic cell size, which is almost one-tenth of the corresponding wavelength of 2.4 GHz obtained in the proposed design. Achieved attenuation levels are around 20 dB for TE and TM polarizations at all incidence angles. Besides, the use of identical geometries on each layer enables the structure to be optimized at 2.4 GHz and 5.8 GHz resonance frequencies independently due to reduced mutual inductance between the layers. The obtained thickness of the structure is only 1.6 mm, which also gives the possibility of using this design as a structural surface material for blocking the ISM signals.

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