A Square Loop Frequency Selective Surface Parametric Study for EC Model Optimisation

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***Abstract*—This paper presents results of an extensive parametric study, based on Electromagnetic simulation, for square loop type frequency selective surfaces (FSS). Consideration was given to the physical attributes of the FSS, such as the loop dimensions and spacing, substrate thickness and dielectric properties, for several frequencies and plane wave incident angles. Correlation analysis and evaluation of input parameters on the FSS performance were performed, yielding to a refinement of the corresponding commonly used equivalent circuit (EC) model. The latter, allows for better estimates of the frequency response of such (canonical) FSS structures. A correction factor for the classical formulation is proposed, in which prediction errors are significantly reduced from 18% to 6% in presented cases. A 6GHz in-house fabricated FSS prototype is also measured in an anechoic chamber, with results being in good agreement to the simulations.**

***Keywords*— Frequency selective surface (FSS), indoor radio communication, radio propagation, simulation.**

I. INTRODUCTION

In the past years, the world has witnessed a significant increase in wireless devices operating at various frequencies across the usable spectrum range [1]. However, in some situations, one may want to block the usage of some devices in favour of others. In office buildings, a company may desire to block mobile phone coverage, while allowing the use of its internal Wi-Fi system and in residential urban environments, one user may want to minimise the interference of his/her Wi-Fi system onto the nearest neighbour's systems [1, 2].

Frequency selective surfaces (FSS) can therefore perform an important role in this topic, contributing to interference mitigation and wireless security in indoor radio environments. Although FSS are envisaged to be used to selectively confine radio propagation in indoor areas, by artificially increasing the radio transmission loss naturally caused by building walls, it may also be applied to other areas of interest [2].

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II. SQUARE LOOP FSS DESIGN AND PARAMETRIC SETUP

The square loop, or square ring FSS design, is a canonical design when it comes to understanding the behaviour of this kind of structures. It has a reject band frequency response, which depends on its physical dimensions. The relatively simple shape makes it ideal to build a prototype for performance assessment. Fig. 1a presents a square loop structure.

The equivalent circuit (EC) model offers a simple and fast method in FSS analysis, which stands as a good alternative to full wave simulations. It is based on a transmission line analogy, in which the FSS is modelled by equivalent inductive (L) and capacitive (C) lumped components. The values for L and C are calculated based on a quasi-static EC approximation of conducting strips developed by *Markuvitz* [3]. Fig. 1b shows the EC model used for the square loop FSS. For Transverse Electrical (TE) wave incidence, the vertical strips act as inductive impedance in the equivalent circuit, and the horizontal gratings as capacitive impedance.

The L and C values of the EC circuit are commonly calculated using equations (1) and (2), where d, p, s and g are the dimensions of the square loop of Fig. 1a [3 - 6].

$$\frac{X_L}{Z_0} = \omega L = \frac{d}{p}\cos\theta\, F(p, 2s, \lambda, \theta), \tag{1}$$

$$\frac{B_C}{Z_0} = \omega C = 4\frac{d}{p}\sec\theta\, F(p, g, \lambda, \theta)\varepsilon_{eff}, \tag{2}$$

where,

$$F(p, w, \lambda, \theta) = \frac{p}{\lambda}\left[\ln\left(csc\frac{\pi w}{2p}\right) + G(p, w, \lambda, \theta)\right] \tag{3}$$

$$G(p, w, \lambda, \theta) = \frac{1}{2}\frac{(1-\beta^2)^2\left[\left(1-\frac{\beta^2}{4}\right)(A_+ + A_-) + 4\beta^2 A_+ A_-\right]}{\left(1-\frac{\beta^2}{4}\right)+\beta^2\left(1+\frac{\beta^2}{2}-\frac{\beta^4}{8}\right)(A_+ + A_-)+2\beta^6 A_+ A_-} \tag{4}$$

with,

$$A_{\pm} = \frac{1}{\sqrt{\left[1 \pm \frac{2p\sin\theta}{\lambda} - \left(\frac{p\cos\theta}{\lambda}\right)^2\right]}} - 1 \tag{5}$$

$$\beta = \sin\left(\frac{\pi w}{2p}\right) \tag{6}$$

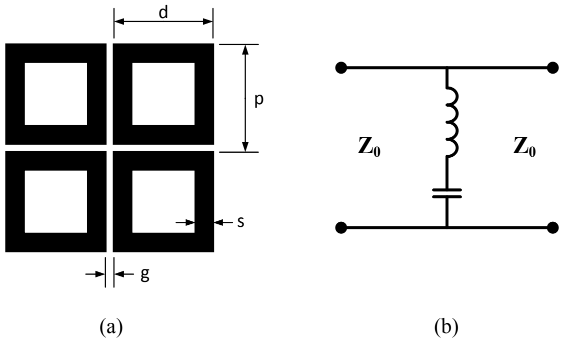

Figure 1. Square loop: a) FSS design; b) EC model.

The value ε_{eff} in equation (2) was not present in previous publications, however it was used in [6] with the value $\varepsilon_{eff}=0.5(\varepsilon_r+1)$. This parameter is intended to be used as an effective dielectric permittivity adjustment value. However, it was found through several simulations that the presence or absence of this adjustment value is only accurate for situations where either the dielectric substrate is very thick ($>\lambda/5$), or is very thin ($<\lambda/100$). The EC equations that are based on [3] have however limitations regarding their validity, such as: $w/p \ll 1$, $p/\lambda \ll 1$ and $p(1+\sin\theta)/\lambda < 1$. However, even if these conditions are met, and depending on substrate size and properties, these equations may lead to inaccurate results.

Assuming an FSS with dimensions: d = 20 mm, s = 5 mm and g = 2 mm, equations (1) and (2) without the ε_{eff} parameter, result in a resonance frequency of 7.77 GHz. Alternatively using ε_{eff} for a FR4 substrate (ε_r = 4.4), one obtains a resonant frequency of 4.73 GHz. This is a substantial difference despite of the substrate thickness, and as such, it undermines the EC simulation results.

The objective of this work was to develop a set of parametric simulations for the square loop FSS, for several values of d, p, s and g, as well as the substrate thickness and permittivity value. With this set of results, a different ε_{eff} equation is to be obtained, which no longer accounts for the effective dielectric permittivity only, but also the effects of the FSS dimensions, while maintaining the core equations.

The parametric simulations were performed on an EM simulator (EMS) for the range of dimensions $d=[16,32]mm$, $s=[4,12]mm$ and $g=[1,6]mm$. The substrate thickness was varied from 0.01mm up to 20mm, and the relative permittivity value of the substrate from 1.5 up to 8.

III. SIMULATION RESULTS

As it was explained above, parametric simulations were aiming to develop an empirical equation to replace the ε_{eff} factor used in [6].

After appropriate empirical equation fittings for the gathered data, more specifically the resonance frequency for each simulation, equation (7) was obtained.

$$\varepsilon_{Corr} = \frac{\varepsilon_r+1}{2} - \frac{\varepsilon_r-1}{2}\exp\left(-h\frac{5p}{(p+2s)\left(s+\frac{g}{2}\right)}\right) \qquad (7)$$

Equation (7) depends on the square loop dimensions (p, s and g), the substrate thickness (h) and the substrate relative permittivity (ε_r). With this ε_{Corr} factor applied to (1) and (2), better approximations between full wave simulations and the EC model were obtained when compared to the original EC model (without this correction factor), or even with the ε_{eff} value shown in [6].

Table I presents a comparison between the full wave simulation and the EC formulation with ε_{eff} and ε_{Corr} factors for different FSS unit cell sizes, with a constant substrate thickness of 1mm and $\varepsilon_r = 4.4$. As can be seen, in a worst case scenario the prediction errors were reduced from 18% to 6%, while in another simulation an error of 0.5% was obtained.

TABLE I. COMPARISON OF SIMULATION RESULTS

FSS unit cell size (mm)	Simulation tool	Resonance frequency (GHz) for incidence angle theta		
		0°	30°	60°
d = 16, s = 2, g = 2	EMS	**4.67**	**4.62**	**4.56**
	Classic EC	6.49	6.32	6.01
	EC with ε_{eff}	4.08	4.05	3.98
	EC with ε_{Corr}	**4.44**	**4.39**	**4.3**
d = 16, s = 3, g = 2	EMS	**6.1**	**5.69**	**5.32**
	Classic EC	8.43	7.87	-
	EC with ε_{eff}	5.6	5.47	5.25
	EC with ε_{Corr}	**6.17**	**5.99**	**5.69**
d = 20, s = 2, g = 4	EMS	**3.85**	**3.84**	**3.76**
	Classic EC	5.21	5.04	4.75
	EC with ε_{eff}	3.3	3.26	3.19
	EC with ε_{Corr}	**3.7**	**3.65**	**3.55**
d = 20, s = 4, g = 2	EMS	**4.93**	**4.75**	**4.49**
	Classic EC	6.32	6.12	5.75
	EC with ε_{eff}	4.04	4	3.92
	EC with ε_{Corr}	**4.78**	**4.71**	**4.57**
d = 24, s = 4, g = 4	EMS	**4.0**	**3.87**	**3.68**
	Classic EC	5.1	4.88	4.52
	EC with ε_{eff}	3.28	3.23	3.15
	EC with ε_{Corr}	**3.94**	**3.85**	**3.7**

IV. MEASUREMENT SETUP

To evaluate the simulation results, a 6GHz reject band FSS prototype was built. The chosen unit cell dimensions for the FSS were d = 16 mm, s = 3 mm and g = 2 mm. The prototype was etched in a 51 by 50 cm FR4 substrate with 1.5mm in thickness and $\varepsilon_r = 4.4$. Fig. 2 depicts the prototype.

In order to properly measure the FSS prototype in the anechoic chamber, a support structure was devised. As can be seen in Figs. 3 and 4, the support structure for the FSS prototype measures 1.8m in height and 2m in width, and it has been covered on its front with pyramidal RF absorbents and in the back with aluminium foil paper. With this structure, diffraction contamination is minimised, and the transmission mainly occurs in the centre square window, which measures 50cm in side. On the transmitter side a wide band horn antenna, with approximately 50° of -3dB beamwidth was used, at a distance of 1.5m from the FSS. On the receiver side, i.e. back side of the support structure, and at the same 1.5m away from the FSS, a low profile ultra wide band antenna was used. The receiver antenna has an omnidirectional pattern in its azimuth plane, which is not the ideal solution since it can receive signals from other incoming directions. This limitation on the receiver side was the main reason for building a large support structure. Figs. 5 and 6 depict the FSS already installed on the support structure.

The frequency response of the prototype was assessed resorting to a Vector Network Analyser (VNA) directly connected to both antennas, by 2m and 15m length cables. Three measurements were performed with the above mentioned setup. A measurement with the window unobstructed, from this point forward designated as free-space (FS) measurement, another measurement with an aluminium metal plate covering the window, and finally one with the FSS under test.

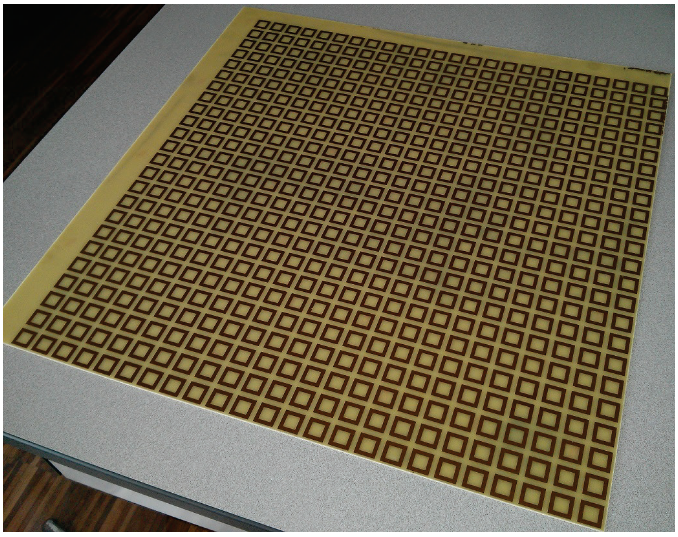

Figure 2. 6GHz reject band FSS prototype.

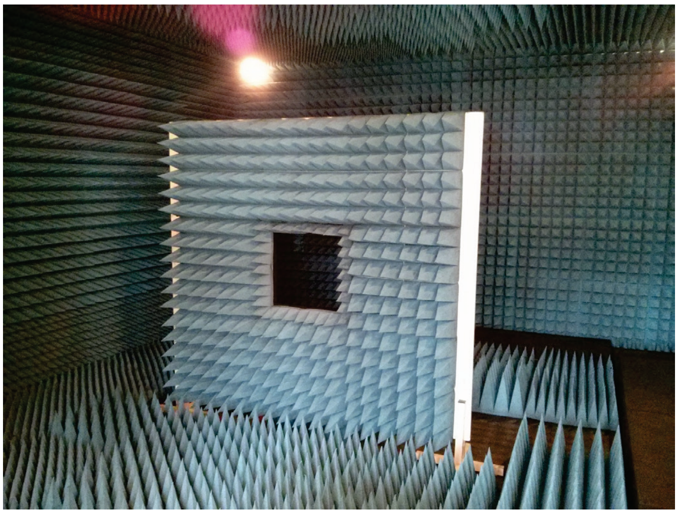

Figure 3. Front view of FSS support structure.

Figure 4. Back view of FSS support structure.

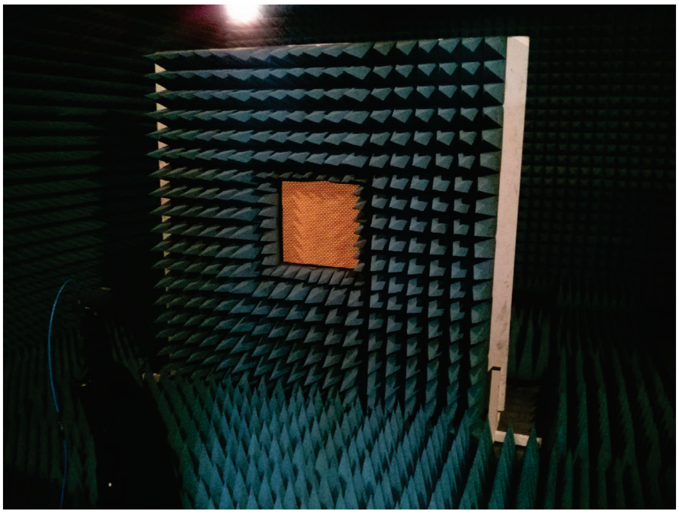

Figure 5. Reject band FSS under measurement.

V. Measurement Results

With the measurement setup defined and assembled, all the necessary measurements were performed in the allowed time frame. Fig. 6 presents the measurement results for the aluminium metal plate setup, but with the S_{21} magnitude values referenced to the FS setup measurement. One can extrapolate from this figure that the dynamic range for the FSS performance assessment is in the range of 25 up to 50 dB. The high variation visible in Fig. 6 may also indicate the presence of contaminated results due to diffraction around the support structure or even to line of sight propagation through small gaps between the RF absorbents.

Fig. 7 depicts the results for the FSS against the EM simulation. As can be seen, the frequency responses are in good agreement, despite the contaminated results of the FSS measurement.

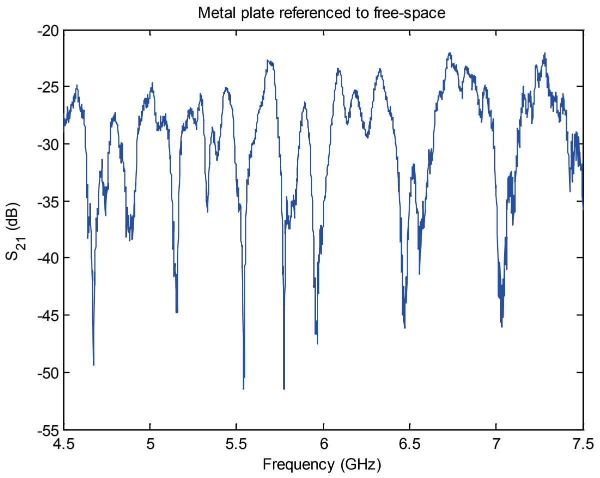

Figure 6. Metal plate setup normalised to FS measurement.

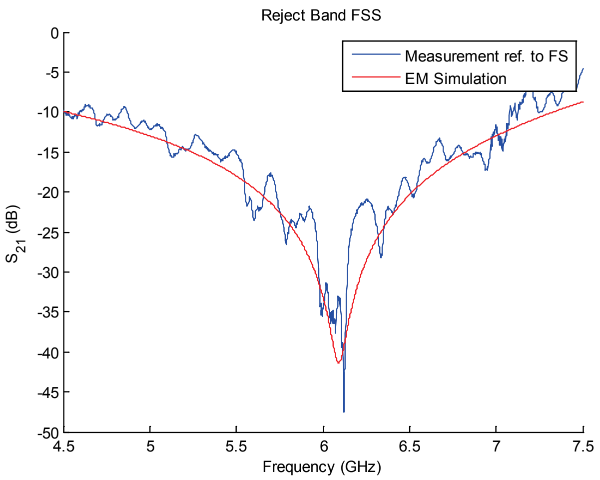

Figure 7. Comparison between measurement and simulations results.

VI. Conclusions

This paper proposes improvements to the EC equations commonly used to model a square loop FSS. A correction factor allowing better estimation of the resonance frequency by taking into account the substrate thickness and other influences caused by the FSS unit cell dimensions is presented, producing errors in the order of 0.5% up to 6% in depicted cases.

By analysing the measurement results and comparing them with the simulations, it can be seen that both EM and EC (with ε_{Corr} factor) simulations provide good estimations to the FSS frequency response. More specifically, and resorting to Table I, the herein proposed correction factor provides better agreement than both classic EC and EC and ε_{eff} factor simulations.

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