Equivalent Circuit Modeling of Frequency-Selective Surfaces Based on Nanostructured Transparent Thin Films

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Abstract **—The equivalent circuit modeling of frequency selective surfaces (FSSs) made of optically transparent metal patches is proposed. The developed procedure allows a simple design of a FSS with the required electromagnetic (EM) performances. The circuit results are validated by numerical simulations of different field configurations.**

I. INTRODUCTION

Optically transparent electromagnetic shields are used in several industrial sectors, e.g. displays of video terminals, windows of transport systems as trains, aircraft, and cars. Using shield panels with a uniform structure composed by metallic multilayers with thickness of few nanometers, the EM field attenuation is quite constant in the entire radio frequency spectrum [1]. Aim of this work is to design frequency-selective surfaces (FSSs) [2], which must be optically transparent having good EM shielding performances for the whole radiofrequencies with the exception of one or more frequency bands. This problem has been addressed in the past using conducting patches of silver and dielectric photonic band gap coating [1]. Here, a circuit approach to modeling multilayer FSS structures is presented. The proposed formulation can be very useful in the design process of the shielding configurations, which can be analyzed as a series-cascade of single-layer FSS structures by the transmission line theory. The originality of the proposed procedure consists mainly in the extraction of the circuit parameters characterizing nanostructured transparent FSS and in the circuit modeling of losses.

II. FSS EQUIVALENT CIRCUIT

The field propagation through a FSS is characterized by the transmission coefficient $T = E^t/E^i$ or by the shielding effectiveness $SE = -20log_{10}(T)$, where E^i, H^i , and E^t, H^t are respectively the incident and transmitted field components tangential to the shield surface.

The configuration of the considered single-layer band-pass FSS is shown in Fig. 1(a). The unit cell has a structure with squared island loading inside the aperture [2]. This configuration acts as a band-pass filter for the incident electromagnetic field. The transmitted field depends on the frequency, polarization and incidence angle of the incident field, and on the aperture geometry and thickness of the unit cell. This band-pass FSS configuration has been intensively studied in the past assuming both the aperture frame and the island to be composed of perfect electrically conductor (PEC) material. Here, in order to realize transparent shields, metal thin films are utilized instead of PEC. Three different test cases are considered: a) PEC frame-PEC island; b) PEC frame-island covered by thin film; c) frame and island covered by thin film.

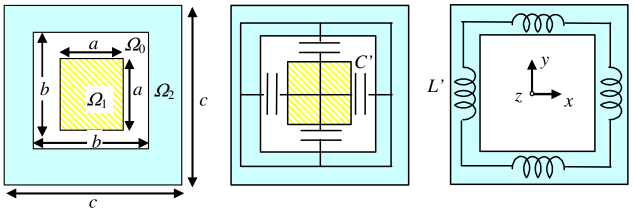
The equivalent two-port network of a single-layer FSS can be modeled in the frequency domain by a shunt admittance Y only. Assuming both frame and island composed by PEC, Y can be approximated by a parallel connection of the equivalent capacitance C between frame and island, and inductance L of the frame [2]. To obtain approximate values of C and L electrostatic and magnetostatic problems must be solved.

The electrostatic circuit configuration is shown in Fig. 1(b) where the island is placed inside a square frame introducing parasitic capacitances C' between the island and the four bars. The electrostatic potential in the island is imposed to be $V_o = 1$ V, while the frame is considered to be grounded. Then the electrostatic energy W_e is calculated by a 3D Finite Element Method (FEM) simulation and the total capacitance C^* is obtained as $C^*= 2\ W_e$. The lumped capacitances for a square island are then obtained as $C' \cong C^*/4$. For a vertically polarized incident field, only the two capacitances between the island and the horizontal bars of the frame must be considered, so the resulting capacitance C is given by the series connection of the two capacitances and is approximately given by $C = C' / 2 = C^* / 8$.

The magnetostatic circuit configuration is shown in Fig. 1(c), where the bars are modeled by the partial inductances L' and the island is not considered since it is quite transparent to the magnetic field. For a vertically polarized incident field, the partial inductances L' can be derived by $L' = 2L_a$ being L_a the aperture inductance [3]-[4]. L_a is calculated by a 3D FEM simulation applying a unit magnetic field H_x on the aperture as unique excitation. The magnetic flux Φ_x of the field $B_x = \mu H_x$ is calculated on the plane $y = 0$ for $z > 0$. Then it yields $L_a = \Phi_x/bH_x$. The final circuit inductance L is given by the parallel connection of the two vertical bar inductances L' as $L = L' / 2$.

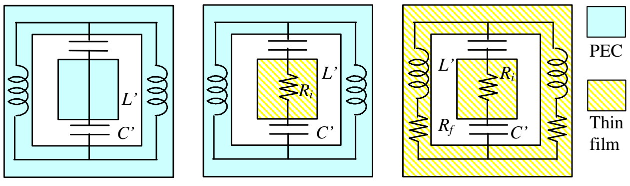
The resistances of the thin film frame square R_f with thickness d, external length c and internal length b can be assumed to be approximated by the dc resistance of the parallel vertical bars due to the nanometer dimension of d. Also the resistance of the thin film square island R_i can be approximated by the dc resistance.

Assuming a vertically polarized incident field, the proposed equivalent circuits for the three test cases described above are shown in Figs. 2 and 3.



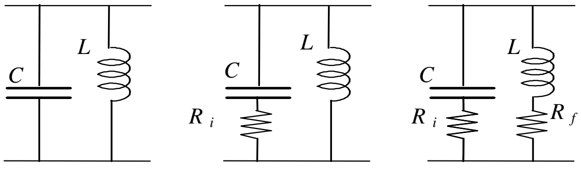
(a) (b) (c)

Figure 1. Band-pass FSS unit cell configuration composed by a frame with four bars and an island (a). Electrostatic (b) and magnetostatic (c) circuit configurations of the unit FSS cell.



(a) (b) (c)

Figure 2. Circuit-parameter configurations of the FSS unit cell for a vertically polarized incident electric field. (a) PEC island and frame. (b) Thin film island and PEC frame. (c) Island and frame covered by thin film.



(a) (b) (c)

Figure 3. Equivalent circuits of the unit FSS cells in Fig. 2.

III. APPLICATION

The band-pass FSS having the geometrical configuration shown in Fig. 1(a) is considered assuming $s = 29.6$ mm, $a = 3s$, $b = 5s$, $c = 6s$, and silver thin film with thickness $d = 68$ nm and $\sigma = 7.76\cdot10^6$ S/m. The metallic areas are considered to be PEC or covered by thin film. The numerical calculations are performed in the frequency domain by using a full-wave FEM procedure with Impedance Network Boundary Conditions (INBCs) [5]. A single FSS cell is analyzed in 3D considering an impinging plane wave with normal incidence. Figure 4 shows the computed frequency spectra of the transmission coefficient T for different FSS configurations. The computed SE is reported in Fig. 5 which shows that the resonant frequency f nearly equal to 900 MHz is quite independent on the losses. Also the influence of the metal thin film thickness is not very relevant.

The lumped parameters of the equivalent circuits in Fig. 3 assume the following values: $L = 44.3$ nH, $C = 0.71$ pF, $R_f = 11.3\ \Omega$ and $R_i = 1.89\ \Omega$. For a vertically polarized incident electric field, the equivalent circuit shown in Fig. 6 is analyzed in the frequency domain assuming the admittance Y to be modeled by the shunt parameters shown in Figs. 3(b) and (c). The circuit resonance is found at $f = 897$ MHz. The circuit and FEM simulations are compared in Fig. 7 revealing a very good agreement.

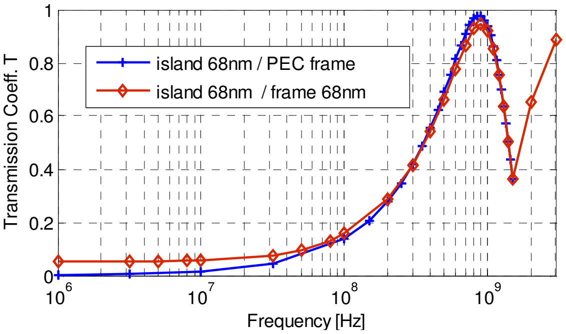


Figure 4. Computed frequency spectra of the transmission coefficient T by full-wave FEM simulations for different FSS configurations.

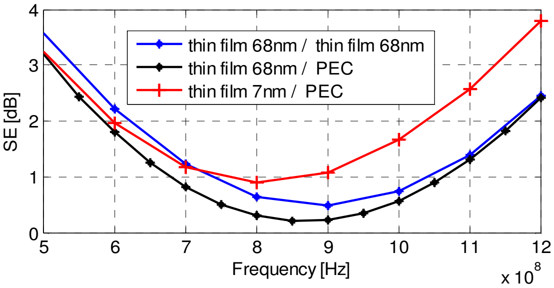


Figure 5. Computed frequency spectra of SE by full-wave FEM simulations for FSS different materials of island / frame near the resonance frequency .

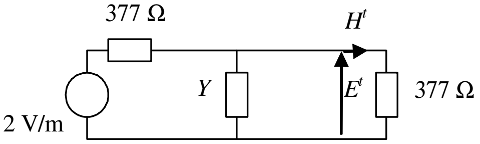
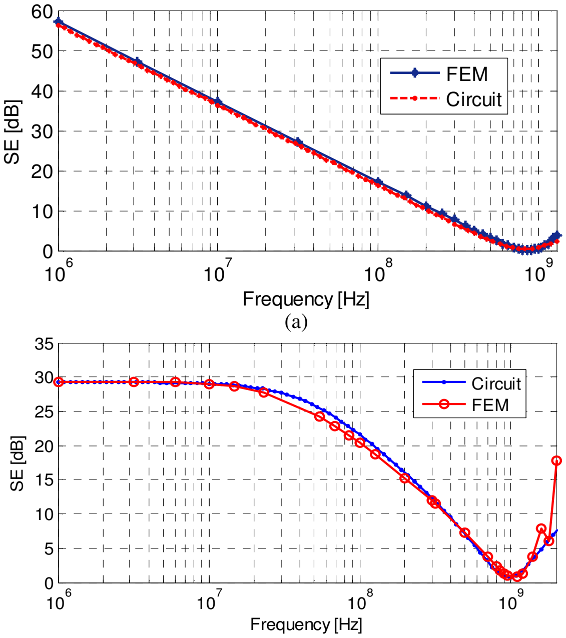


Figure 6. Equivalent circuit of a unit FSS cell for a vertically polarized electric field.



(b)

Figure 7. Computed frequency spectra of SE by FEM and circuit approaches for PEC frame and silver thin film island (a), and for both silver thin film frame and island (b).

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