Design and Analysis of Frequency Selective Surfaces Loaded with Lumped Elements for Secure Wireless Indoor Networks Using Split-field Update FDTD Method

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Abstract

The work presented in this paper concerns incorporating lumped elements including resistor, capacitor and inductor into the split-field update FDTD analysis of periodic structures and presenting a new single resonance within a wide range of frequency band, miniaturized and stable resonance structure with lumped inductor elements analyzed using this method. Results are in very good agreement with those obtained by the frequency domain finite element method.

Introduction

Frequency Selective Surfaces are very popular structures in spatial filtering of electromagnetic waves. They have been used in many applications such as radomes, dichroic sub-reflectors, photonic band gap structures and artificial magnetic conductors. Recent uses of frequency selective surface include military applications, antennas and telecommunications and wireless security. For wireless security in buildings, a conventional FSS is placed in the wall of the buildings to provide isolation between adjacent vicinities [1-2].However when used as a band-stop filter in walls of buildings, a conventional FSS may reject some higher order resonance frequencies that is not favorable. Furthermore the unit cell size in a conventional FSS is large for low frequency band wireless communications and the performance degrades when the size of the building wall in one direction is small. For narrowband wireless applications, it is necessary that FSS exhibits stable resonance in different incidence angles that is not attainable with a conventional FSS. Lumped elements including inductor and capacitor at microwave and millimeter wave frequencies are now available and can be used in high frequency band periodic structures such as frequency selective surfaces [2] and artificial magnetic conductors. In this paper lumped elements are used in the FSS structure as an alternative approach to achieve all these features simultaneously. Because these structures are needed to be analyzed over a wide range of frequency band, fast time domain methods are preferred rather than the frequency domain methods. Several time domain methods have been presented for the analysis of periodic structures. Split-field update FDTD method introduced in [3] is one of the most powerful methods. Here, lumped elements formulations are incorporated in this method formulation based on [4] and the proposed structure is analyzed using this method.

Method Formulation

The proposed method for including lumped elements in the split-field method is presented in this section for 3D case. Here a parallel *RLC* is considered. When a parallel *RLC* is inserted into the FDTD space lattice, the Maxwell's curl $\overrightarrow{H}$ equation becomes [4]:

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$$\nabla \times \overrightarrow{H} = \frac{\partial \overrightarrow{D}}{\partial t} + \overrightarrow{J}_{Res} + \overrightarrow{J}_{Cap} + \overrightarrow{J}_{Induc} \tag{1}$$

Assuming a z-directed parallel RLC we have:

$$J_{z-Res} = \frac{dz}{Rdx\,dy}E_z \;; \quad J_{z-Cap} = \frac{Cdz}{dx\,dy}\left(\frac{\partial E_z}{\partial t}\right) \;; \quad J_{z-Induc} = \frac{dz}{L\,dx\,dy}\int_0^t E_z\,dt \tag{2}$$

A periodic structure in y and z directions is considered and lumped elements are x, y or z-directed that is defined by an index. Using (1) and (2), the 3D transformed field equations with lumped elements for *P* components are given by:

$$\begin{aligned} \frac{\varepsilon_r}{c}\frac{\partial P_x}{\partial t} + \sigma\eta_0 P_x = {} & \frac{\partial Q_z}{\partial y} - \frac{\partial Q_y}{\partial z} - \frac{\overline{k}_y}{c}\frac{\partial Q_z}{\partial t} + \frac{\overline{k}_z}{c}\frac{\partial Q_y}{\partial t} - \frac{dx}{c\varepsilon_0 R_x dydz}P_x - \frac{C_x dx}{c\varepsilon_0 dy\,dz}\left(\frac{\partial P_x}{\partial t}\right) \\ & - \frac{c\mu_0 dx}{L_x\,dy\,dz}\int_0^t P_x\,dt \end{aligned} \tag{3}$$

$$\begin{aligned} \frac{\varepsilon_r}{c}\frac{\partial P_y}{\partial t} + \sigma\eta_0 P_y = {} & -\frac{\partial Q_z}{\partial x} + \frac{\partial Q_x}{\partial z} - \frac{\overline{k}_z}{c}\frac{\partial Q_x}{\partial t} - \frac{dy}{c\varepsilon_0 R_y dxdz}P_y - \frac{C_y dy}{c\varepsilon_0 dx\,dz}\left(\frac{\partial P_y}{\partial t}\right) \\ & - \frac{c\mu_0 dy}{L_y\,dx\,dz}\int_0^t P_y\,dt \end{aligned} \tag{4}$$

$$\begin{aligned} \frac{\varepsilon_r}{c}\frac{\partial P_z}{\partial t} + \sigma\eta_0 P_z = {} & \frac{\partial Q_y}{\partial x} - \frac{\partial Q_x}{\partial y} + \frac{\overline{k}_y}{c}\frac{\partial Q_x}{\partial t} - \frac{dz}{c\varepsilon_0 R_z dxdy}P_z - \frac{C_z dz}{c\varepsilon_0 dx\,dy}\left(\frac{\partial P_z}{\partial t}\right) \\ & - \frac{c\mu_0 dz}{L_z\,dx\,dy}\int_0^t P_z\,dt \end{aligned} \tag{5}$$

The transformed field equations for *Q* components do not change. By defining new variables, the extra time derivatives on the right hand side can be eliminated. In [3] the fields in the directions of the structure periodicities are split into two components. Here, UPML absorbing boundary condition is used. For similar periodic boundary conditions for "a" portions of the fields in the UPML region and non-UPML region, the field components in the direction of the structure periodicities are split into three components as for the UPML region [5]. New variables must be defined as follows:

$$P_x = P_{xa} + \frac{\overline{k}_z}{\varepsilon_r + \dfrac{C_x dx}{\varepsilon_0 dydz}}Q_y - \frac{\overline{k}_y}{\varepsilon_r + \dfrac{C_x dx}{\varepsilon_0 dydz}}Q_z \tag{6}$$

$$P_y = P_{ya} + P_{yb} - \frac{\overline{k}_z}{\varepsilon_r + \dfrac{C_y dy}{\varepsilon_0 dxdz}}Q_x \tag{7}$$

$$P_z = P_{za} + P_{zb} + \frac{\overline{k}_y}{\varepsilon_r + \dfrac{C_z dz}{\varepsilon_0 dxdy}}Q_x \tag{8}$$

Substituting these variables into the systems (3-5) results in:

$$\left(\frac{\varepsilon_r}{c}+\frac{C_x dx}{c\varepsilon_0 dydz}\right)\frac{\partial P_{xa}}{\partial t}+\left(\sigma\eta_0+\frac{dx}{c\varepsilon_0 R_x dydz}\right)P_{xa}=\frac{\partial Q_z}{\partial y}-\frac{\partial Q_y}{\partial z}+\frac{\sigma\eta_0+\frac{dx}{c\varepsilon_0 R_x dydz}}{\varepsilon_r+\frac{C_x dx}{\varepsilon_0 dydz}}\overline{k}_y Q_z$$

$$-\frac{\sigma\eta_0+\frac{dx}{c\varepsilon_0 R_x dydz}}{\varepsilon_r+\frac{C_x dx}{\varepsilon_0 dydz}}\overline{k}_z Q_y-\frac{c\mu_0 dx}{L_x dydz}\int_0^t P_{xa}dt-\frac{\overline{k}_z}{\varepsilon_r+\frac{C_x dx}{\varepsilon_0 dydz}}\frac{c\mu_0 dx}{L_x dydz}\int_0^t Q_y dt \tag{9}$$

$$-\frac{\overline{k}_y}{\varepsilon_r+\frac{C_x dx}{\varepsilon_0 dydz}}\frac{c\mu_0 dx}{L_x dydz}\int_0^t Q_z dt$$

$$\left(\frac{\varepsilon_r}{c}+\frac{C_y dy}{c\varepsilon_0 dxdz}\right)\frac{\partial P_{ya}}{\partial t}+\left(\sigma\eta_0+\frac{dy}{c\varepsilon_0 R_y dxdz}\right)P_{ya}=-\frac{\partial Q_z}{\partial x}-\frac{c\mu_0 dy}{L_y dxdz}\int_0^t P_{ya}dt \tag{10}$$

$$\left(\frac{\varepsilon_r}{c}+\frac{C_y dy}{c\varepsilon_0 dxdz}\right)\frac{\partial P_{yb}}{\partial t}+\left(\sigma\eta_0+\frac{dy}{c\varepsilon_0 R_y dxdz}\right)P_{yb}=\frac{\partial Q_x}{\partial z}+\frac{\sigma\eta_0+\frac{dy}{c\varepsilon_0 R_y dxdz}}{\varepsilon_r+\frac{C_y dy}{\varepsilon_0 dxdz}}\overline{k}_z Q_x \tag{11}$$

$$-\frac{c\mu_0 dy}{L_y dxdz}\int_0^t P_{yb}dt-\frac{\overline{k}_z}{\varepsilon_r+\frac{C_y dy}{\varepsilon_0 dxdz}}\frac{c\mu_0 dy}{L_y dxdz}\int_0^t Q_x dt$$

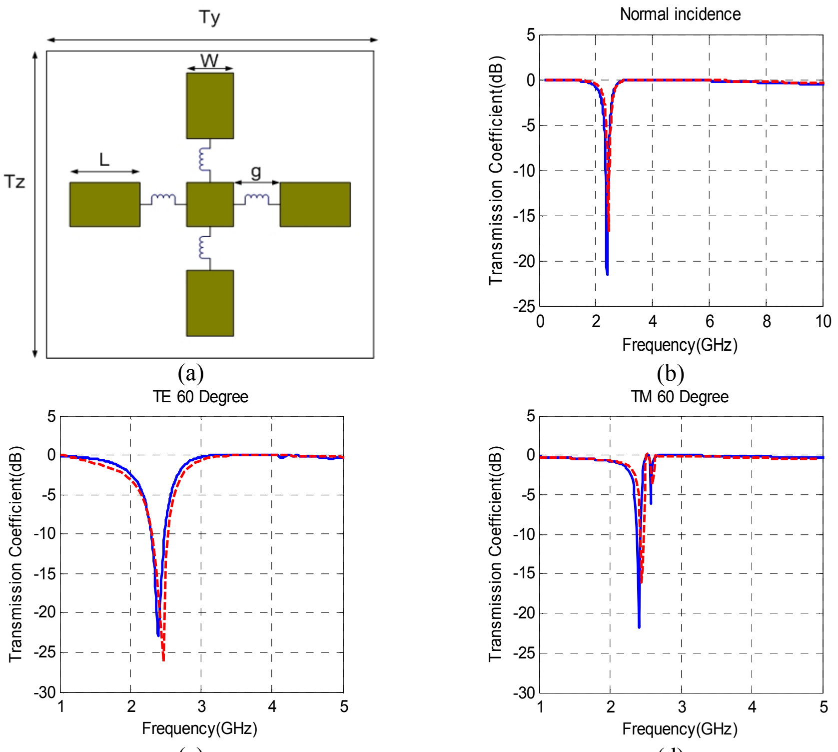
P_{za} and P_{zb} are updated similarly . Once "a" and "b" portions are updated the new values of the x-component are found using (6) and the remaining field components are found from (7), (8). The stability factor condition does not change and is explained in [3].

Numerical Results

The configuration of a frequency selective surface with cross dipole elements incorporating four $15\,nH$ ceramic chip inductors in each unit cell for rejecting the 2.4 GHz wireless local area network signals is showed in Fig.1(a).The unit cell size is $14mm\times 14mm$ and a substrate of $2mm$ thick and $\varepsilon_r = 2.65$ is used. The transmission coefficients of this structure for different plane waves from $1GHz$ to $10GHz$ are illustrated in Fig.1 (b-d). The only resonance frequency in this frequency band is $2.4GHz$ and there is no other resonance frequency up to $18GHz$ .Also the unit cell size is reduced greatly in comparison with the analogous FSS without lumped elements. The maximum shift in resonance frequency in this structure is 0.04%, while this value for a conventional cross dipole at this frequency is about 15 %.

Conclusion

A new FSS structure with chip lumped inductors is proposed and analyzed using split-field update FDTD method for secure wireless indoor networks. The results agree with



(a) (b)

(c) (d)

Fig. 1:(a) Geometry of the FSS structure with ceramic chip inductors (Ty,Tz,L,W,g)=(14,14,3,2,2)mm. Transmission coefficient for different plane waves. Split-field FDTD (solid lines) and FEM (dashed lines) (b) Normal incidence (c) TE 60 degree (d) TM 60 degree.

those obtained by the frequency domain finite element method. The proposed structure is miniaturized considerably and exhibits stable resonance with respect to polarization and incidence angle in comparison with a conventional cross dipole FSS. Furthermore higher order resonance frequencies near the dominant resonance frequency are eliminated that makes the structure suitable for secure wireless indoor networks, because the higher order resonance may occur at the other wireless communication frequency bands.

Acknowledgments

This work was supported by Iran Telecommunication Research Center.

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