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Design of wide-bandwidth electromagnetic wave absorbers using the inductance and capacitance of a square loop-frequency selective surface calculated from an equivalent circuit model

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ABSTRACT

The design of wide-bandwidth microwave absorbers is conducted using a square loop-frequency selective surface (SL-FSS) on the surface of the grounded dielectric substrate. The parallel circuit combination of the input impedance of the grounded substrate and the complex impedance of the SL-FSS leads to impedance matching in a broad frequency range. The inductance (L) and capacitance (C) of the SL-FSS is calculated using the equivalent circuit model, which is dependent on the SL-FSS geometry. For the SL-FSS, the inductance and capacitance are calculated from the equations of reactance and susceptance at the resonance frequency (f_0) of the equivalent L–C circuit. The circuit is capacitive below f_0 and inductive above f_0. For a grounded substrate with a quarter wavelength thickness, however, the input impedance is inductive at lower frequencies and capacitive at higher frequencies. Through combining these two impedances, impedance matching can be derived over a wide frequency range with the controlled FSS resistance matched to the free-space impedance. The optimized surface resistance of the FSS conductor is $R_s = 26\ \Omega$ for the widest bandwidth (4.9–16.4 GHz with respect to -10 dB reflection loss), which is consistent with the simulation results obtained via computational tool.

1. Introduction

A frequency selective surface (FSS) is a two-dimensional periodic single or multi-planar structure formed using a large number of passive resonant units on the dielectric layer [1,2]. They are periodic arrays of conducting patches or aperture elements that have a certain frequency-selective characteristics of electromagnetic waves from microwaves to optics. In recent years, resistive FSSs have been widely used to design broadband absorbers through the equivalent circuit mode, and numerical optimizations have been proposed in order to design radar absorbing materials (RAMs) [3–13]. The equivalent circuit parameters of FSS (resistance (R), inductance (L), and capacitance (C)), which primarily depend on the form of resonant cell (patch, cross, square loop, etc.), periodic distribution, and surrounding medium, have key functions in the design of broadband RAMs.

Various methods for analyzing the periodic structures have been developed with computational approaches such as the mutual impedance method [1], the method of moments [14], the finite element method (FEM) [15], and the equivalent circuit method [16,17]. Using the equivalent circuit method, which is a simple and efficient technique, FSSs can be modeled as energy-storing inductive or capacitive components that are determined by the shape and geometry of their elements.

In this paper, we provide a reliable and efficient analytical method for the design of broadband absorbers with a square loop-frequency selective surface (SL-FSS), based on the equivalent circuit model. For the SL-FSS, the inductance and capacitance are calculated using the equations of reactance and susceptance of the equivalent L–C circuit at the resonance frequency. The admittance analysis is conducted for the SL-FSS and grounded dielectric substrate with variations in the surface resistance of the SL-FSS conductor strips. Through parallel circuit combinations of the two admittances, impedance matching can be derived over the wide frequency range with a controlled FSS resistance matched to the free-space impedance.

2. Inductance and capacitance of SL-FSS

The inductance (L) and capacitance (C) of the SL-FSS can be calculated using the equivalent circuit model [16,17], which is dependent on the SL-FSS geometry. Fig. 1 illustrates the SL-FSS standing in free space (with a characteristic impedance

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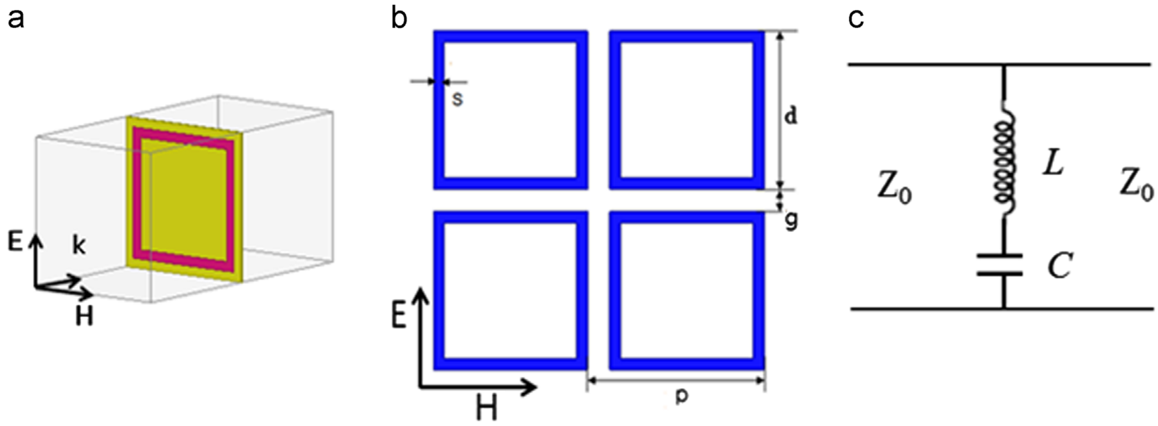

Fig. 1. Schematic description of the (a) SL-FSS standing in free space, (b) dimensions of the unit cell ($p=10$ mm, $d=8.75$ mm, $s=0.625$ mm, and $g=1.25$ mm), and (c) equivalent circuit.

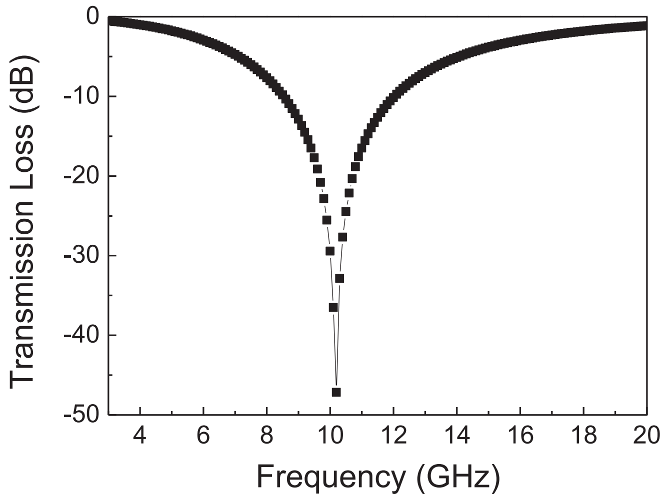

Fig. 2. Simulation results of the transmission loss of the SL-FSS standing in free space.

$Z_0=377\ \Omega$), its dimensions, and the equivalent circuit. The dimensions of the unit cell period ($p=10$ mm), SL-FSS (length (d)= 8.75 mm, width (s)=0.625 mm), and two SL-FSS interval spacing ($g=1.25$ mm) are given in Fig. 1(b). If the resistance of the FSS conductor is zero (i.e. a perfect conductor), the circuit can be represented by a shunted L–C series circuit, as depicted in Fig. 1(c). When an electromagnetic wave (with a wave vector k) is incident normal to the composite structure, perfect reflection (transmission=0) occurs at the resonance frequency due to the zero impedance of the SL-FSS. A computational tool (High Frequency Structure Simulator (HFSS) 13.0) was used to determine the transmission loss for the SL-FSS structures illustrated in Fig. 1(a). It can be seen from the simulation results in Fig. 2 that this array has a single principal resonance at a frequency (f_0) of 10.2 GHz.

In the equivalent circuit model where the square loop array is represented by a single series L–C circuit shunted across a transmission line of impedance of free space, a shunt inductive reactance (X_L) and a capacitive susceptance (B_C) were provided in the article [16]. The modeling technique is based on the equations given by Marcuvitz [17] for the impedance of periodic arrays of thin continuous conducting strips, and it can be used where the element geometry may be recognized as consisting of inductive and capacitive components.

The equivalent circuit inductive reactance (X_L) is given by:

$$\frac{X_L}{Z_0}=\frac{\omega L}{Z_0}=\frac{d}{p}\frac{p\cos\theta}{\lambda}\left[\ln\left(\csc\left(\frac{2s\pi}{2L}\right)\right)+G\right], \tag{1}$$

where ω is the angular frequency, θ is the incident angle, λ is the wavelength at the resonance frequency, and G is correction factor given in Eq. (2).

$$G=\frac{1}{2}\frac{\left(1-\beta^2\right)^2\left[\left(1-\frac{\beta^2}{4}\right)(A_1+A_2)+4\beta^2A_1A_2\right]}{\left(1-\frac{\beta^2}{4}\right)+\beta^2\left(1+\frac{\beta^2}{2}-\frac{\beta^4}{8}\right)(A_1+A_2)+2\beta^6A_1A_2} \tag{2}$$

$$\beta=\sin\frac{2\pi s}{2p} \tag{3}$$

$$A_{1,2}=\frac{1}{\sqrt{1\pm\frac{2p\sin\theta}{\lambda}-\left(\frac{p\cos\theta}{\lambda}\right)^2}}-1 \tag{4}$$

The correction factor G is involved in the equivalent circuit equation, which reflects the effects of incidence angle θ, period p and width s of conducting strips with respect to the wavelength at resonance frequency λ, as depicted in Eq. (2). When θ is small (i.e. normal incidence) and the period is small relative to the wavelength ($p/\lambda \ll 1$), the correction factor can be neglected ($G\approx 0$).

The equivalent circuit capacitive susceptance (B_c) is given as follows:

$$\frac{B_c}{Y_0}=\frac{\omega C}{Y_0}=\frac{4d}{p}\frac{p\cos\theta}{\lambda}\left[\ln\left(\csc\left(\frac{\pi g}{2L}\right)\right)+G\right], \tag{5}$$

where Y_0 is the admittance of free space ($=1/Z_0$) and the correction factor G is given using Eq. (2), where β is a function of g (spacing between two SL-FSS):

$$\beta=\sin\frac{\pi g}{2p} \tag{6}$$

The reactance and susceptance are reduced by a factor of d/p from the corresponding array of infinite strips in order to consider the finite strip length.

For the SL-FSS with the geometry illustrated in Fig. 1(b), the inductance and capacitance were calculated to be $L=2.965$ nH and $C=83.45$ fF, respectively. With these L and C values, the resonance frequency was calculated to be $f_0=1/[2\pi(LC)^{1/2}]=10.26$ GHz, which is consistent with the simulation result in Fig. 2.

3. Design of an absorber with the SL-FSS

Fig. 3 illustrates the structure of a microwave absorber