Impedance Modeling for a Unit Cell of the Square Loop Frequency Selective Surface at 2.4 GHz

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***Abstract*— Equivalent Circuit (EC) method gives a simple alternative method in Frequency Selective Surface (FSS) analyses which are useful for quickly predicting the characteristic of FSS. An impedance modeling of the Equivalent Circuit (EC) for a unit cell of the square loop FSS structure is presented in this paper. The unit cell of the square loop FSS is designed and simulated using the CST Microwave Studio software at 2.4 GHz based on industrial, scientific and medical bands (ISM) standard. The square loop FSS is simulated without FSS, with square FSS and square FSS with slot. The investigation has been done on the length of substrate (*s*), width of substrate (*w*), length of square FSS (*a*) and length of square FSS with slot (*b*). Real (Re) and Imaginary (Im) component of EC or known as resistance and reactance has been modeled based on physical parameters of the design structure of the FSS. The resistance and reactance of the impedance are depending on the geometry of the unit cell of FSS. This impedance modelling can be used to design the advance FSS for the similar ISM band. EC gives a simple alternative method in FSS analyses which are useful for quickly predicting the performance of FSS.**

Keyword- Equivalent Circuit (EC), Frequency Selective Surface (FSS), impedance modeling, square loop FSS, reactance, resistive

I. INTRODUCTION

Metamaterials have properties that may not be found in nature. It gains its properties not from their composition but from their designed structures. It consists of periodic structure and subwavelength characteristic which particle smaller than the light wavelength with which it interacts. Others are structured that exhibit the subwavelength characteristics are Frequency Selective Surface (FSS) or also known as Artificial Magnetic Conductor (AMC) or High Impedance Surface (HIS) [1]. FSS is a planar periodic structure of identical arrays of patch or aperture type elements arranged in one or 2D plane. FSS have inherent inductive and capacitive properties that useful in designing to get a desired frequency response. Its filtering characteristic is depending on the array element type [2-6].

The frequency behavior of the FSS is entirely determined by the geometry of the surface in one period (unit cell), the size of the FSS, the way the surface is exposed to the electromagnetic wave (incidence angle of the incoming wave), substrate parameters, inter-element spacing and materials used. They are various methods to analyze the periodic structures of the FSS such as the mutual impedance method, the method of moments (MoM) [7], the finite element method (FEM) [8], the finite-difference time-domain (FDTD) method and Equivalent Circuit (EC) method [9-13].

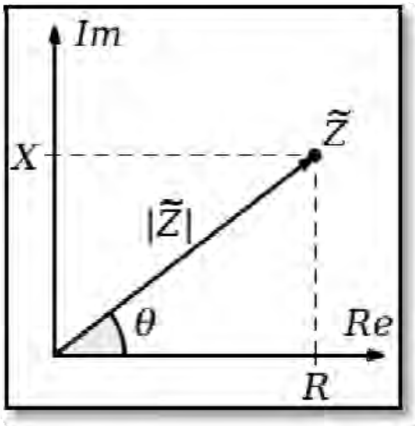
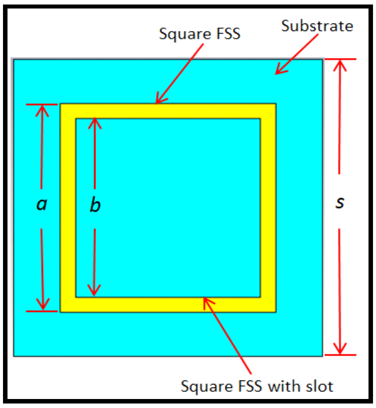


Fig. 1. Complex impedance plan

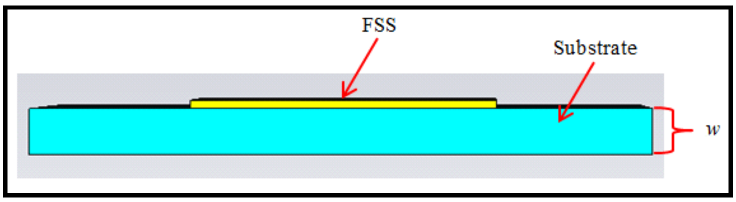
By using Equivalent Circuit method, FSS can be modeled as an energy-storing inductive or capacitive component which is determined by the shape of its elements. At any specific frequency, impedance may be represented by either a series or a parallel combination of an ideal resistive element and an ideal reactive element which is either capacitive or inductive as in Fig. 1. Such a representation is called an equivalent circuit. The values of these elements or parameters depend on which representation is used, series or parallel, except when the impedance is purely resistive or purely reactive. Impedance is a comprehensive expression of any and all forms of opposition to electron flow, including both resistance and reactance. It is present in all circuits, and in all components. When alternating current goes through an impedance, a voltage drop is produced that is somewhere between 0^o and 90^o out of phase with the current. Impedance is one of the important parameters in modeling the FSS by using the EC method [12].

To achieve a certain spectral response for the FSS, many parameters can be adjusted such as the dimensions of periodicity, element shape, dielectric thickness and constant, and number of periodic screens. Equivalent circuit is one of the methods to analyze the performance of the FSS. In the most of the paper published on the FSS design, the impedance of the Equivalent Circuit has not been investigated [10-15]. So, this paper presents the impedance modeling of the Equivalent Circuit for the unit cell of the square loop FSS at 2.4 GHz.

II. FSS DESIGN



(a)



(b)

Fig. 2. Unit cell geometry of the FSS design structure (a) front view (b) side view

The unit cell geometry of the proposed design FSS structure which consists of dielectric substrate and FSS as shown in Fig. 2. The FSS is made up of copper with thickness 0.035 mm etched on the FR4 board (200 mm × 200 mm) with thickness of 1.6 mm, dielectric constant of 4.4 and a tangent loss of 0.019. The physical design structure parameters that have been investigated in this paper are length of substrate (*s*), width of substrate (*w*), length of square FSS (*a*) and length of square FSS with slot (*b*).

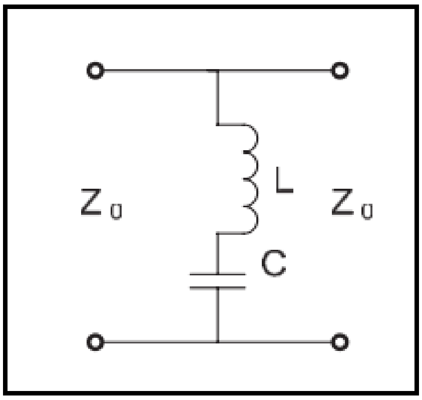


Fig. 3. Equivalent circuit for square loop [10]

By using the well-known circuit theory, the FSS can be equivalently modelled as a resonant circuit consisting of parallel-connected two series L-C resonators as shown in Fig. 3. Reflection coefficient can be represented as Γ is the ratio of the amplitude of the reflected wave to the amplitude of the incident wave. The impedance at the load Z_L can be calculated by using (1). $Z_0$is the impedance of free space (377 Ω) [9].

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{1}$$

The complex impedance, Z can be written as (2) where the real part of the impedance (Re) is resistance, R and the imaginary part of the impedance (Im) is reactance, X.

$$Z = R + jX \tag{2}$$

The reactance, X is the total of the inductive reactance, X_L and capacitive reactance, X_C and the equation of the reactance can be written as (3).

$$X = X_L - X_C \tag{3}$$

The impedance caused by these two effects referred to resistance which is formed the real part and reactance forms the imaginary part of complex impedance. When the reactance is larger than 0, the reactance is said to be inductive while when the reactance is less than 0, the reactance is said to be capacitive. For reactance equal to 0, the impedance is said to be resistive.

III. Simulation Setup

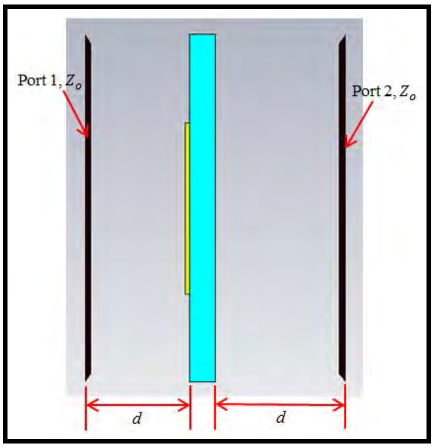


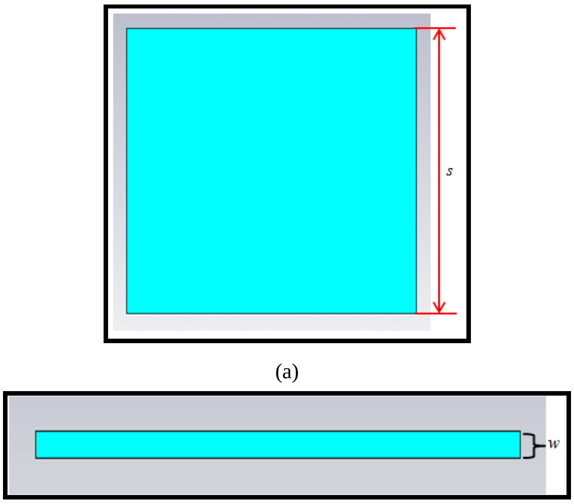
Fig. 4. The distance between substrate with port 1 and port 2 (*d*)

Two waveguide ports have been used to represent the boundary conditions of the calculation domain. The design FSS structure is placed between two waveguide ports. Waveguide ports required enclosing the entire field filled domain in the cross section of the transmission line with the port area. The investigation has been done for various distances to study its effect on the impedance. The distance between the design FSS structure and port (*d*) as shown in Fig. 4 that has been chosen in this paper is 30 mm [17-18]. The waveguide ports in the design represent the Z_0.

The square loop FSS is designed and simulated by using CST Microwave Studio at 2.4 GHz. There are three types of configuration for this simulation that will be investigated. The length that has been investigated in this paper is from 0 mm to 3 mm. First configuration is a dielectric substrate without FSS structures. The width (*w*) and the length (*s*) of the dielectric substrate are investigated. The dielectric substrate that has been used in this paper is FR4 board. Second configuration is a dielectric substrate with square FSS structures and third configuration is a dielectric substrate with square FSS with slot. The length of the square FSS (*a*) and the length of the square FSS with slot (*b*) has been investigated. Then, the impedances of the Equivalent Circuit are modeled for each configuration. The impedance is modeled by using polynomial type in Matlab. The impedances are divided into the certain length so that an accurate impedance modeling is produced.

IV. Results and Discussion

A. Without FSS



(a)

(b)

Fig. 5. FR4 board (a) front view (b) side view

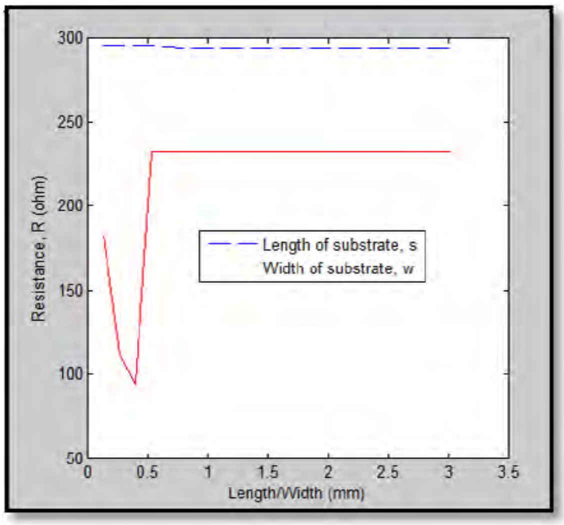


Fig. 6. Resistance versus parameters *s* and *w*

The length of substrate (*s*) and width of substrate (*w*) are investigated as shown in Fig. 5. There are smaller changes of the resistance when the length (*s*) and the width (*w*) of substrate are varied as shown in Fig. 6. The resistance of the FSS is decreased for *w* between 0.2 to 0.4 mm while the resistance is increased from 90 Ω to 230 Ω from 0.4 to 0.5 mm. After that, the resistance remains at 240 Ω at parameter *w* more than 0.5 mm. However, the changes of parameter *s* will not affect the resistance of FSS. The highest degree of the resistance of the FSS is 4th degree polynomial. The resistance modelling of the FSS is written as (4) to (7).

i. *Length of substrate, s*

$$R \begin{cases} 376.7s^4 + 619.6s^3 - 360.3s^2 + 84.56s + 288.8 & s < 0.5 \quad (4) \\ -5.29e^{-14}s + 293.7 & 0.5 < s < 3 \quad (5) \end{cases}$$

ii. *Width of substrate, w*

$$R \begin{cases} -5.529e^4w^4 + 8.026e^4w^3 - 3.788e^4w^2 + 6575w - 192.9 & w < 0.5 \quad (6) \\ -1.322e^{-14}w + 232.2 & 0.5 < w < 3 \quad (7) \end{cases}$$

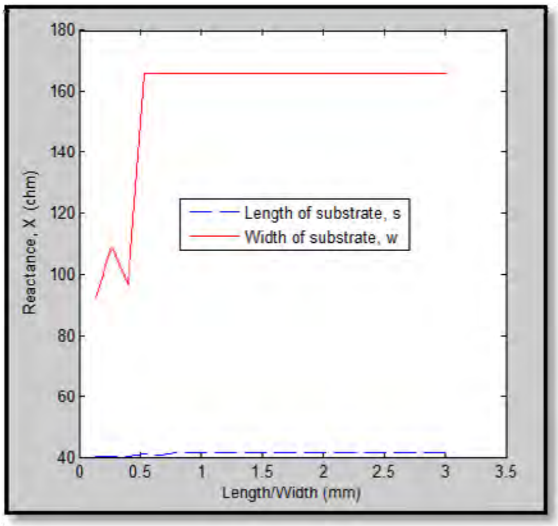


Fig. 7. Reactance versus parameters *s* and *w*

From the graph as shown in Fig. 7, the reactance is remained at 40 Ω for all values of parameter *s* while the reactance remains at 164 Ω for parameter *w* more than 0.5 mm. When the parameter *w* is increased from 0 to 0.2 mm, the reactance also increased from 95 Ω to 109 Ω. Then, the reactance is decreased from 109 Ω to 98 Ω when parameter *w* between 0.2 to 0.5 mm. The highest degree of the reactance for parameter *s* is cubic while for parameter *w* is a 4th degree polynomial as in (8) to (12).

i. *Length of substrate, s*

$$X \begin{cases} 59.59s^3 - 51.13s^2 + 13.5s + 39.24 & 0 < s < 0.5 \quad (8) \\ 3.969s + 38.19 & 0.5 < s < 1 \quad (9) \\ -6.64e^{-15}s + 41.32 & 1 < s < 3 \quad (10) \end{cases}$$

ii. *Width of substrate, w*

$$X \begin{cases} -3.659e^4w^4 + 5.629e^4w^3 - 2.944e^4w^2 + 6179w - 328.2 & 0 < w < 0.5 \quad (11) \\ -3.967e^{-14}w + 166.1 & 0.5 < w < 3 \quad (12) \end{cases}$$

B. With square FSS and square FSS with slot

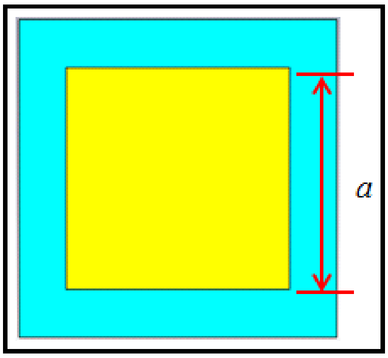


Fig. 8. Design structure of square FSS

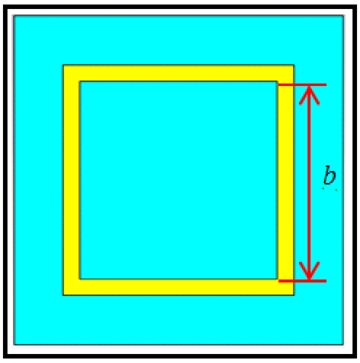


Fig. 9. Design structure of square FSS with slot

In this part, the second and third configurations have been investigated. Second configuration is the investigation of the length of square FSS (*a*) and the third configuration is the investigation of the length of the square FSS with slot (*b*) as shown in Fig. 8 and Fig. 9.

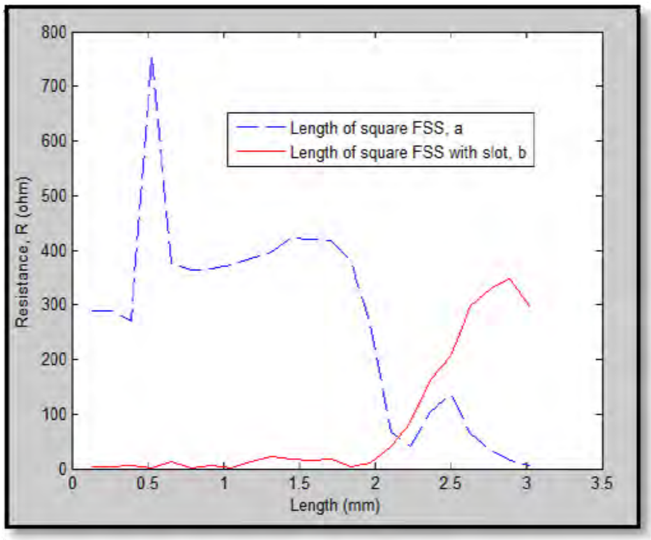


Fig. 10. Resistance versus parameters *a* and *b*

The effect of the length of the square FSS (*a*) and the length of the square FSS with slot (*b*) are shown in Fig. 10. The resistance of FSS is fluctuated for parameter *a*. The highest resistance that has been found by parameter *a* and parameter *b* is 750 Ω at length of 0.5 mm and 350 Ω at length of 2.8 mm respectively. Parameter *a* provided the larger resistance of FSS compared to the parameter *b*. Then the highest degree of the resistance for parameter *a* is a 4th degree while for parameter *b* is a 6th degree as in (13) to (18).

i. *Square FSS, a*

$$R = \begin{cases} 3.864e^4a^3 - 3.11e^4a^2 + 7600a - 261.2 & 0 < a < 0.5 \quad (13) \\ 432a^2 - 721.9a + 644 & 0.5 < a < 1 \quad (14) \\ 6367a^4 + 3.247e^4a^3 - 6.16e^4a^2 - 5.163e^4a - 1.578e^4 & 1 < a < 2 \quad (15) \\ 0.776e^{-0.53a} + 0.754 & 2 < a < 2.5 \quad (16) \\ 337.7a^2 - 2060a + 3148 & 2.5 < a < 3 \quad (17) \end{cases}$$

ii. *Square FSS with slot, b*

$$R = -58.99b^6 + 473.6b^5 + 1400b^4 + 1914b^3 - 1232b^2 + 340b - 25.92 \qquad 0 < a < 3 \qquad (18)$$

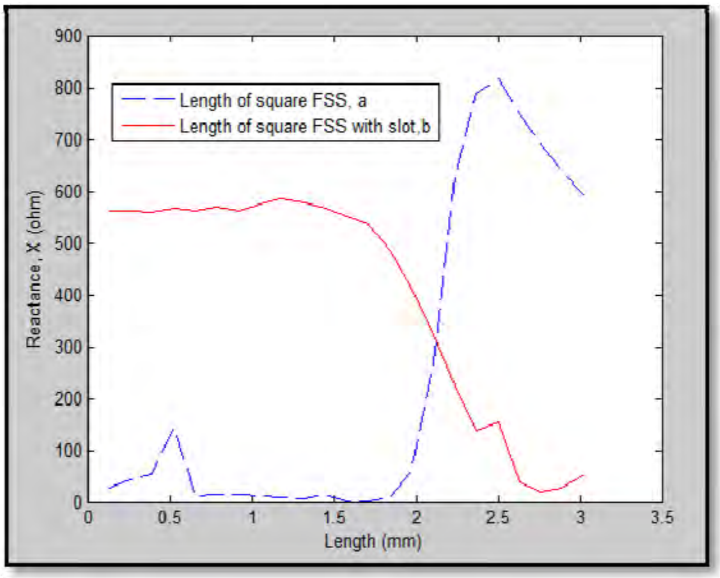


Fig. 11. Reactance versus parameters *a* and *b*

The reactance of the FSS is affected by parameter *a* and parameter *b* as shown in Fig. 11. The graph is shown the reactance of the FSS for parameter *a* vice versa with the parameter *b* at length between 1.8 to 2.4 mm. The reactance of the FSS for parameter *a* is increased from 0 to 740 Ω while reactance of the FSS for parameter *b* is decreased from 540 to 140 Ω. The highest reactance is 820 Ω which is achieved by parameter *a* at length of 2.5 mm. The reactance modelling are as in (19) to (23).

i. *Square FSS, a*

$$X = \begin{cases} 5754a^3 - 4611a^2 + 1232a - 66.67 & 0 < a < 0.5 \quad (19) \\ 1327a^6 - 9645a^5 + 2.846e^4a^4 - 4.356e^4a^3 + 3.638e^4a^2 - 1.571e^4a + 2752 & 0.5 < a < 2 \quad (20) \\ 8.48e^{-2}(e^{-0.266a}) + 0.677 & 2 < a < 2.5 \quad (21) \\ -400.8a + 1801 & 2.5 < a < 3 \quad (22) \end{cases}$$

ii. *Square FSS with slot, b*

$$X = -42.4b^6 + 444.2b^5 - 1678b^4 + 2794b^3 - 2116b^2 + 672.4b + 497.7 \qquad 0 < a < 3 \qquad (23)$$

V. CONCLUSION

This paper is presented the impedance modelling of the Equivalent Circuit for unit cell of the square loop FSS at 2.4 GHz. The resistance and the reactance modelling of the FSS are based on the physical parameters of the design structure which are the length of substrate (*s*), width of substrate (*w*), length of square FSS (*a*) and length square FSS with slot (*b*). The modelling is based on linear, quadratic, cubic, 4th degree and 6th degree polynomial type by using Matlab software. The highest degree of the resistance and reactance is achieved by parameter *b* with the degree of 6th.This model can be used to design the FSS at the similar ISM band. Experimental works, including fabrication and measurement of the FSS, are under way in our research laboratory to verify the theoretical design and evaluation.

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