Modeling and Design of Frequency Selective Surface for GSM and UMTS Frequency Bands

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Abstract:

In this paper, frequency selective surfaces (FSSs) are analyzed and designed. The simulation and analysis of different configurations of loop elements based FSS is proposed. A simple technique of Single-Square-Loop frequency selective surface (SSL-FSS) is used. The process of the calculation of various parameters is presented and the numerical technique has been supported by the simulation. The simulations of microstructure are performed with full wave simulation tool CST-Microwave Studio on single substrate for different physical parameters. The results show that the transmission improvement at 900 MHz, 1800 MHz and 2100 MHz of GSM and UMTS frequency bands. Regardless of unknown electric characteristic of aluminum and substrate, the transmission curve of free standing Triple Square Loop FSS, it has three band pass response with center frequency 945 MHz, 1785 MHz and 2.4GHz.

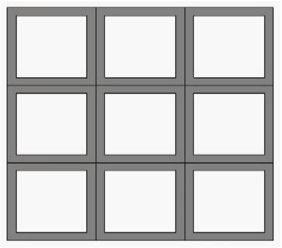
Keywords:equivelent circuit model; frequency selective surface; square loop.

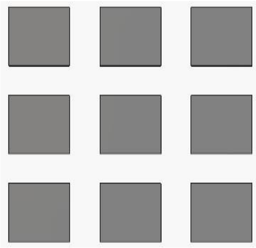
I. INTRODUCTION

A frequency selective surface (FSS) is a spatial electromagnetic filter, which is defined as a one or two dimensional periodic array of patch elements or aperture elements etched on a dielectric substrate. The geometries of both patch and aperture elements are shown in Fig. 1.

The most common FSS element shapes include simple straight dipole, circular loop, cross dipole, three-legged dipole, square loop and Jerusalem Cross. Depending on the physical construction and geometry of the surface, the FSS can efficiently control the transmission and reflection of the incident electromagnetic plane wave and may have low pass, high pass, band pass and band stop behaviors [1].

The underlying theory of FSS has evolved from the research on diffraction gratings which is carried out by the American physicist David Rittenhouse in 1786. The pioneering work and intensive investigating on the frequency selective surfaces can be traced to the 1960s. Over the years, frequency selective surfaces have found widespread application in communication, microwave and radar systems for more than four decades. The typical application of FSS is applied to the radome to reduce the radar cross section (RCS) of antennas at the out-of-Band frequency.





Patch element *Aperture element*

Fig. 1. *Geometries of patch and aperture elements FSS array*.

II. EQUIVALENT CIRCUIT MODELS

The EC model offers a simpler alternative method in FSS analyses. Based on a transmission line analogy, transmission characteristics of an FSS structure can be determined. The FSS is modeled as equivalent inductive and capacitive components in a transmission line, where the circuit components are evaluated based on the quasi-static EC approximation of conducting strips developed by Marcuvitz. Because it is a scalar technique, Although properties of dielectric substrates and signal incident angles can be taken into account in the EC equations, due to assumptions made in the EC approximation, the accuracy provided by the model may vary from case to case [3].

Many studies have successfully employed the EC model in analyzing FSSs with simple element shapes such as square loops, meshes, linear dipoles, and Jerusalem crosses. Despite the less precise analysis offered by this EC approach compared to other methods, the EC model was chosen to be the preferred analyzing tool for this paper. This is because the model provides results acceptably accurate, and most importantly it can quickly characterize FSSs with varying element dimensions [3].

This modeling technique requires minimal computational resources, but provides reasonably accurate and fast predictions for FSSs with simple element shapes. Based on the equivalent inductive and capacitive components evaluated in the Equivalent Circuit model, present the development of the Equivalent Circuit model for SL-FSS. Basic design rules for SL element dimensions are given along with equations for the Equivalent Circuit model.

III. THE SQUARE LOOP ELEMENT

The Square Loop Element (SL) was chosen as the FSS element shape. This is because of the uncomplicated modeling. At the same time, its performance is superior to other element shapes in terms of the angular response stability and the available operating bandwidth. For SL elements, resonance occurs when each half loop acts as a dipole [4].

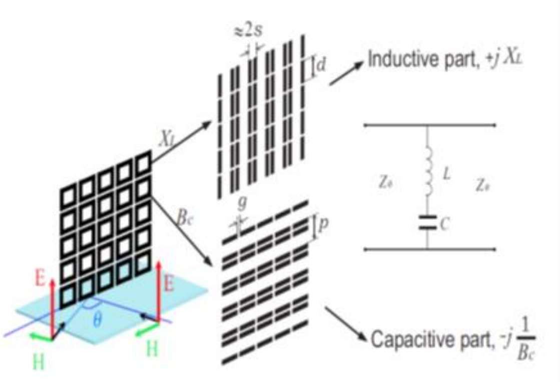


Fig. 2. *The equivalent circuit approximation of the square loop FSS, With TE-wave incidence.*

IV. THE EQUIVALENT CIRCUIT DEVELOPMENT

An FSS layer can be represented by an equivalent circuit in a transmission line analogy as shown in Fig. 2. The square loops are separated into vertical and horizontal conducting strips, which can be modeled respectively as inductive and capacitive components for TE-wave incidence [9].

Evaluation of the L and C components For TE-wave incidence, as indicated in Fig. 2, which has the electric field parallel to the vertical strips, the vertical strips can be modeled as a shunt inductive reactance in the EC circuit.

The normalized impedance value X_l/Z_o is determined as:

$$\frac{X_l}{Z_o} = \frac{\omega L}{Z_o} = \frac{d}{p} cos(\theta)\, F(p, 2s, \lambda, \theta) \qquad (1)$$

Where

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

And

$$G(p,w,\lambda,\theta) = \frac{0.5(1-\beta^2)\left[\left(1-\frac{\beta^2}{4}\right)(A_+ + A_-) + 4\beta^2 A_+ A_-\right]}{\left(1-\frac{\beta^2}{4}\right)+\beta^2(1+\frac{\beta^2}{2}+\frac{\beta^4}{8})(A_+ + A_-)+4\beta^6 A_+ A_-}$$

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

$\beta = \sin\left(\frac{\omega\pi}{2p}\right)$ And λ is the wavelength in air at the operating frequency θ is the incident angle at the FSS, and w is equal to 2s in this calculation.

V. THEORY OF OPERATION SQUARE LOOP FREQUENCY SELECTIVE SURFACES

The equivalent circuit model of a SSL-FSS .is developed by Marcuvitz Equation [3]. This has been used to extract the circuit lumped parameters inductance (L) and capacitance (C) by several researchers. With the help of the equivalent circuit model, the equivalent inductance and capacitance are obtained from the given physical parameters of an FSS like the periodicity (p), loop length (d), width of the strip (w), angle of incidence (θ) and the inter-loop gap (g), where these parameters are shown in Fig. 3.

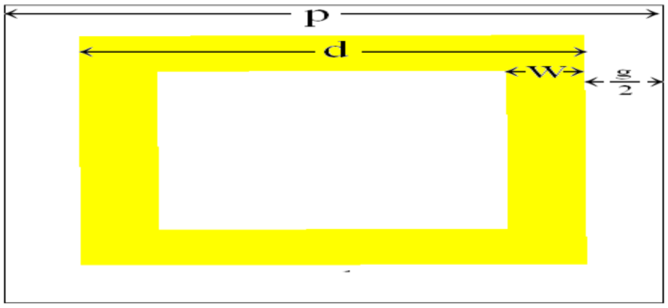


Fig. 3. *FSS Schematic.*

However, in the design, it is desired to find the loop size and periodicity of the loop structure to resonate at the specific frequency and to have the desired bandwidth.

The EC method only provides the knowledge about the value of the L and C. But the accurate synthesis of from the knowledge of the resonance frequency is a challenging task and has not been dealt adequately. A simple and novel formula to calculate the loop dimension with certain accuracy has been developed. For (TE) polarized wave, the equivalent circuit elements are obtained by the following equations

$$\frac{\omega_r L}{Zo} = \frac{d}{p} cos(\theta) \times F(p, w, \lambda, \theta) \tag{2}$$

Where

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

And

$$\frac{\omega_r C}{Yo} = 4\frac{d}{\lambda}\sec(\theta) \times F(p, g, \lambda, \theta)\varepsilon_{eff} \tag{3}$$

Where

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

In Equations (2), (3),ε_{eff}, Zo, Y_o, G (p, w, λ, θ), and G (p, g, λ, θ) are the effective dielectric permittivity of the media, characteristic impedance, characteristic admittance, the correction factors for the associated inductance and capacitance, respectively. When the correction factors are ignored at the cost of a minor deviation in the result, Equations (2) and (3) can be re-written as:

$$\frac{\omega_r L}{Zo} = \frac{d}{p}\cos(\theta) \times \frac{P}{\lambda}\left[\ln \csc\, (\frac{\pi w}{2P})\right] \tag{4}$$

$$\frac{\omega_r C}{Yo} = 4\frac{d}{\lambda}\sec(\theta)\frac{P}{\lambda}\left[ln \csc\, (\frac{\pi g}{2P})\right] \times \varepsilon_{eff} \tag{5}$$

In the case of air as a substrate, the multiplication of Equations (4) and (5) gives:

$$\omega_r^2 LC = 4\left(\frac{d}{P}\right)^2\left(\frac{P}{\lambda}\right)^2 \times ln\left[csc(\frac{\pi w}{2P}) + csc(\frac{\pi g}{2P})\right] \tag{6}$$

In Equation (6), the left-hand-side of the equation indicates the resonance/anti-resonance condition. For the reflective FSS, at the resonance, its value must be 1.0 because $\omega r^2 = 1/LC$. Therefore, Equation (6) can be re-written in the following

$$1 = 4\left(\frac{d}{P}\right)^2\left(\frac{P}{\lambda}\right)^2 \times ln\left[csc(\frac{\pi w}{2P}) + csc(\frac{\pi g}{2P})\right] \tag{7}$$

Further, Equation (2) is simplified as:

$$1 = 4\left(\frac{d}{P}\right)^2\left(\frac{P}{\lambda}\right)^2 \times ln\left[\frac{1}{\sin\,(\frac{\pi w}{2P})} + \frac{1}{\sin\,(\frac{\pi g}{2P})}\right] \tag{8}$$

For the case of w << 2p and g << 2p, Equation (8) is written as:

$$1 = 4\left(\frac{d}{P}\right)^2\left(\frac{P}{\lambda}\right)^2 \times ln\left[\frac{2P}{\pi\omega} + \frac{2P}{\pi g}\right] \quad (9)$$

In the case of the loosely packed FSS, the value of g is quite greater than w and the ratio of $2p/w\pi$ dominates over the ratio of $2p/g\pi$ and with the minor sacrifice in the accuracy, Equation (9) is simplified as:

$$1 = 4\left(\frac{d}{\lambda}\right)^2 \times ln\left[\frac{2P}{\pi w}\right] \quad (10)$$

It is known fact that for a given FSS structure, the response changes with the change in the angle of incidence of the wave and the period p of the FSS and to avoid the grating lobes, it is related to the wavelength λ by the following relationship[12].

$$p(1 + sin\theta) < \lambda \quad (11)$$

VI. FSS Modeling and Simulation

VII. Numerical Results for Square Loop Frequency Selective Surfaces

To analyze the theory for the Square Loop Frequency Selective Surfaces, the physical parameters of FSS at 4 GHz have been compute by Matlap, and its correctness has been checked by the electromagnetic simulation in CST Microwave Studio. To calculate the value of *p* while avoiding grating lobe at the intended frequency, the value of *p* is calculated by meeting the condition descried in Equation (11) and this condition which is for the analysis purpose and $\theta > 0$ needs to be considered. In order to meet this synthesis constraint, the value of θ = 10 has been selected and on this way, the value of *M* is 0.1736. Once, the value of *M* is fixed, for the different value of w/λ, the value of *d* is calculated using the Equation (10) and it is presented in TABLE I, for 4 GHz. Further, to support the analysis, the structure has been simulated by CST Microwave Studio.

The value of the resonance frequency obtained by simulation is shown in 7th column of this TABLE I. it shows he various values of *p*, *d*, and *w* at different frequencies for the normal incidence. From this TABLE I, it is revealed that for the fixed value of *p*, with the increase in the value of w/λ,

The simulated value of S_{21} parameter in frequency range 1-5 GHz is shown in Fig. 4 (a, b, c), show different transmission as mentioned in TABLE I.

TABLE I. PARAMETERS AT 4 GHZ FOR BAND-STOP FILTER.

w/λ	Periodic (P)	Loop length (d)	Strip width (w)	Capacitance C(P)	Inductive L(n)	fr (GHz) simulation
0.01	0.0639	0.0195	0.001	0.0729	14.22	4.18
0.04	0.0639	0.0232	0.003	0.0976	11.93	4.16
0.08	0.0639	0.0271	0.006	0.1283	10.24	4.18

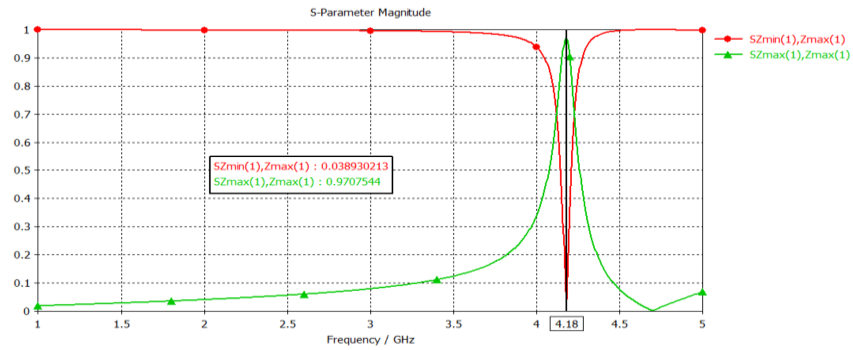


Fig. 4(a) *When width (w=1mm).*

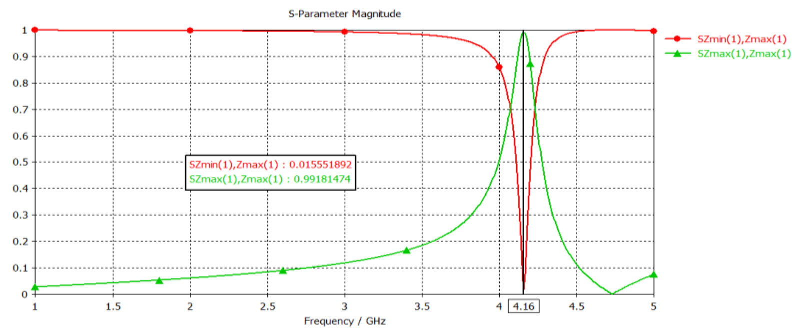


Fig. 4(b) *When width (w=3mm).*

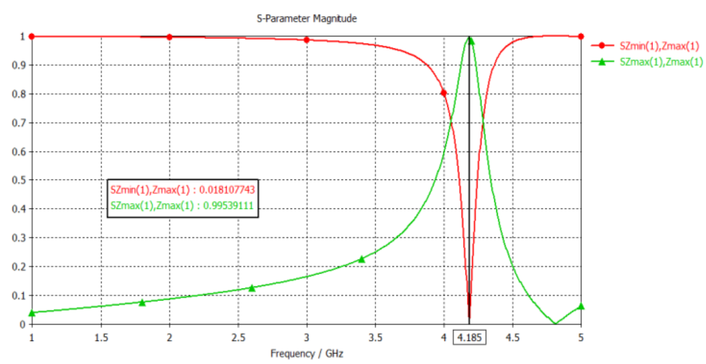
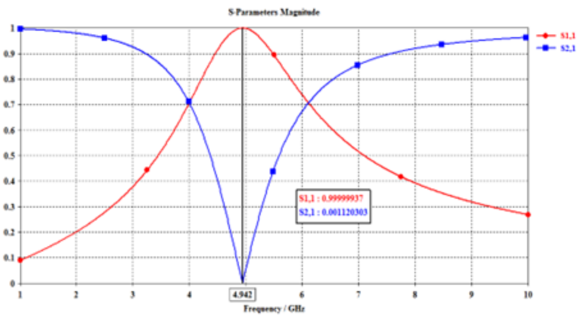


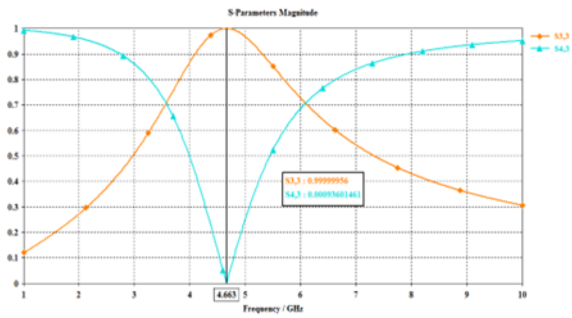
Fig. 4(c) *When width (w=6mm).*

Fig. 4 Transmission *and reflection coefficient of (Band-Stop) design as TABLE I. By cast (Microwave-studio).*

From Fig. 4(d), the equivalent circuit at a given incident angle (10^o in this case), with the increase in the w/λ¸ ratio, the transmission zero point shifts to the lower frequency and the transmission zero bandwidth is increased.



When width (w=1mm).



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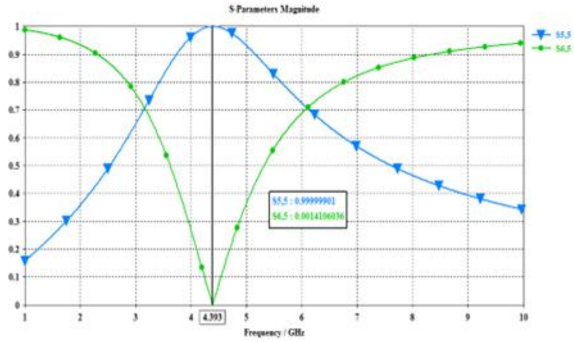
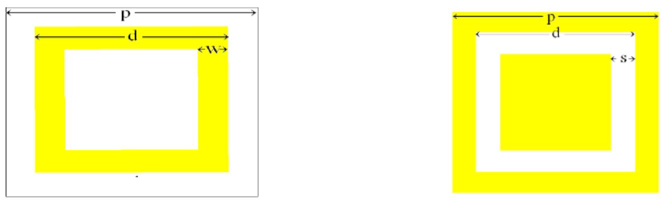


When width (w=6mm).

Fig. 4(d) *Equivalent circuit and response to Band-Stop as present in TABLE I.*

VIII. Extension of the Procedure to Band-pass FSS Design

It is known fact that the band-pass and band-stop FSS are complementary to each other. Due to this nature of the structure, a band-stop FSS structure can be converted into band-pass by replacing the conducting material part by the slot and the vacant part of the FSS by the conductor. In this case, the period p remains same and the width w is replaced by the slot width and d becomes the length of the slot. It indicates that the synthesis process developed in this work is also suitable to find the parameters of the shape band-pass FSS.



a b

Fig. 5. *Frequency selective surface, (a) band- pass and (b) band- stop.*

To see the process of the analysis of the band-pass response, we have designed band-stop and band-pass FSS in frequency bands. In the first case, the value of p, d, and w=s are 63.9 mm, 23.2 mm, and 3 mm, respectively. The parameter values are shown in the TABLE II. and expected resonance frequency in band-pass approximately as well as in the band-stop FSS structure is 4.16GHz. The band-stop and band-pass FSS to resonate at this frequency.

TABLE II. PARAMETERS AT 4 GHZ FOR BAND-BASS FILTER.

w/λ	Periodic (P)	Loop length (d)	Strip width (w)	Capacitance C(P)	Inductive L(n)	fr (GHz) simulation
0.01	0.0639	0.0195	0.001	0.0729	14.22	4.30
0.04	0.0639	0.0232	0.003	0.0976	11.93	4.11
0.08	0.0639	0.0271	0.006	0.1283	10.24	4.12

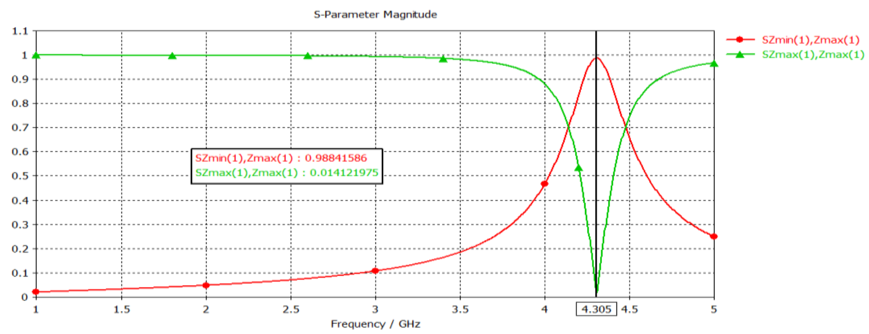


Fig. 6(a) *When width (w=1mm).*

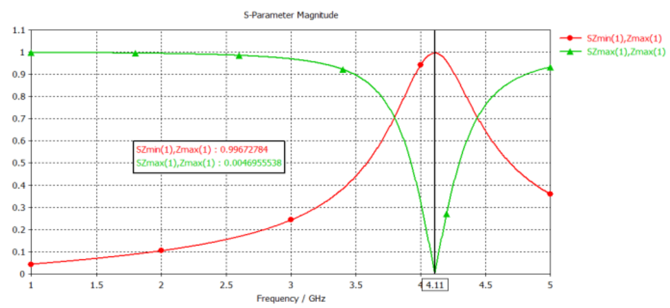


Fig. 6(b), *When width (w=3mm).*

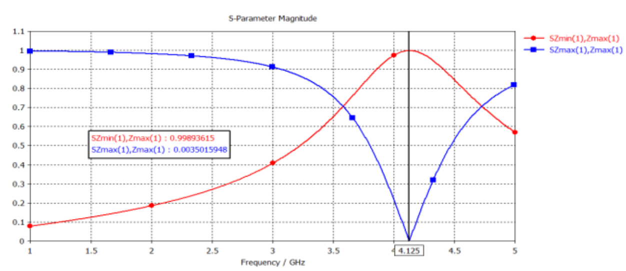
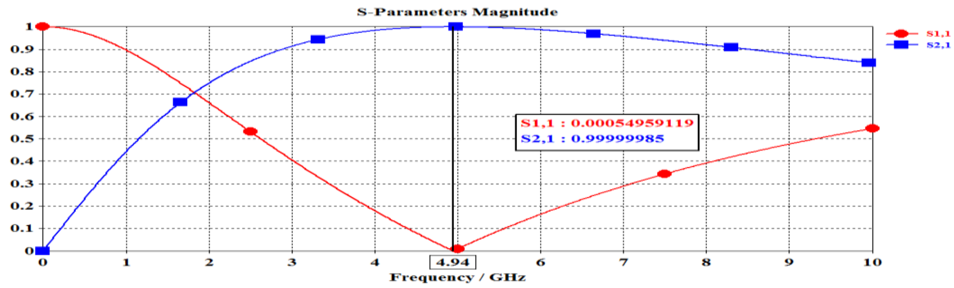
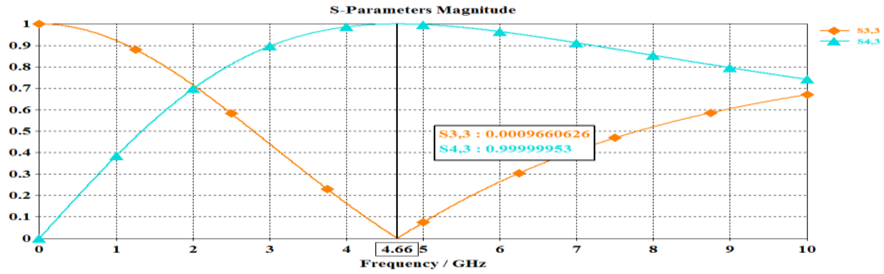


Fig. 6(c) *When width (w=6mm).*

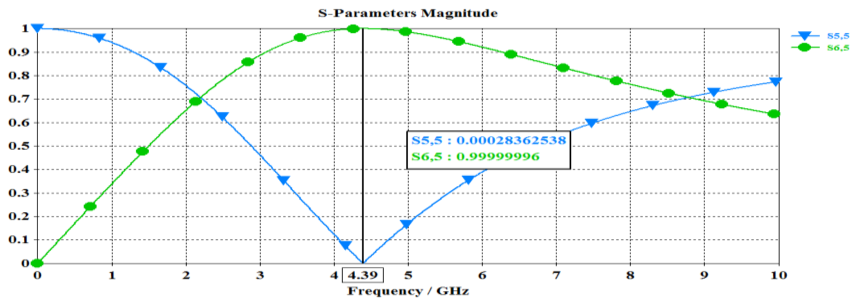
Fig. 6 Transmission *and Reflection coefficient of (Band-Pass) design as TABLE II. By cast (Microwave-studio).*



When width (w=1mm).



When width (w=3mm).



When width (w=6mm).

Fig. 6(d) *Equivalent circuit response of Band-pass as presented in TABLE II.*

IX. FSS MODELING AND SIMULATION TRIPLE SQUARE LOOP

Square loop element shape was chosen for the FSS analysis purpose, due to the structural simplicity and best suitable for all frequency characteristics, the frequency selective characteristics should be triple band-pass. Hence, each band is realized by a square loop aperture element. The dimension of the unit cell of triple square loop aperture FSS is shown in TABLE III. According to dimension of the unit cell shown in Fig. 7, 19.48% of the conducting area is removed from the total area of unit cell.

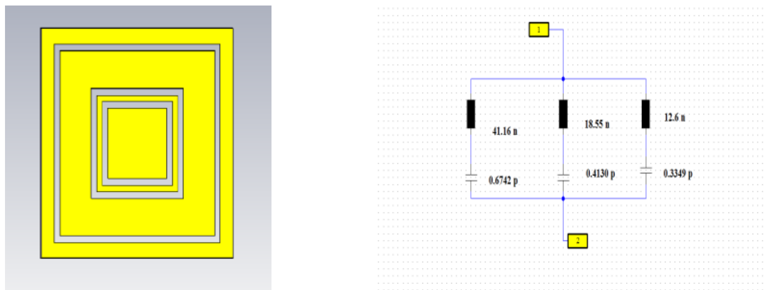


Fig. 7. *Unit cell geometry and equivalent circuit.*

TABLE III. PARAMETERS DESIGN AND RESULTS FOR TRIPLE BAND-PASS

Frequency		900MHz	1800MHz	2.5GHz
Parameter Design	Periodic(P)	100mm		
	Loop length(d)	86.8mm	48.1mm	36.7mm
	Strip width(w)	3mm	3mm	3mm
Results	Reflection R(S_{11})	0.0694	0.1673	0.0394
	Transmission T(S_{22})	0.9976	0.9859	0.9992
	Capacitance C(P)	0.6742	0.4130	0.3349
	Inductive L(n)	41.160	18.550	12.600
	fr (GHz) simulation by (CST-microwave studio)	945.00MHz	1785.0MHz	2.4377GHz
	fr(GHz) by Equations	955.41MHz	1818.3MHz	2.4498GHz

It is a free standing FSS, meaning it has no dielectric material for support. For loop type FSS, resonance occurs when the total length of the loop is approximately one wavelength. The larger square loop aperture was tuned for GSM900 band and a medium loop for GSM1800 and UMTS2100 band and smaller loop for 2.5GHz. Hence, a third band-pass FSS structure was realized which had resonant frequency at 950 MHz and 1800MHz and 2.5GHz. The resonant frequency of 1800 MHz was chosen to cover both the GSM1800 and UMTS 2100 frequency band. The conducting material of FSS was modeled using an aluminum metal in the simulator. A very thin layer of conducting material was realized by using an approximation of zero thickness. The characteristics of the aluminum used to model the conducting part of FSS consists of following parameters: relative permeability =1, electric conductivity = 3.56×107 S/m, thermal conductivity = 237 W/K/m and material density = 2700 kg/m^3.In Fig. 7, yellow part represents the conducting part, and squares represent apertures of 3 mm size each.

X. SIMULATION RESULTS

Fig. 8,(a&b) shows the transmission curve of free standing Triple Square loop FSS. It has three band pass response with center frequency 945 MHz and 1785 MHz and 2.4GHz. The purpose of choosing the 1785 MHz as one center frequency is to cover both 1700 MHz and 2100 MHz frequency. In Fig. 8b, marker 1, 2, 3, 4, 5 and 6 shows the -3 dB point for first and second and third band pass region. The first reading of the each marker shows the frequency in GHz and the second reading shows transmission level in dB. Hence the -3 dB transmission bandwidth for first band-pass region with 945 MHz and second band-pass region with 1785MHz center frequency and third band-pass region with 2.4GHz is 567 MHz and 285 MHz and 353MHz respectively.

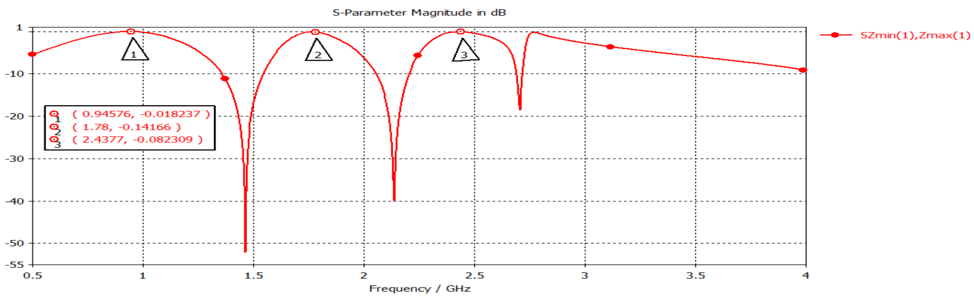


Fig. 8 (a) *Simulated Transmission curve at Triple Square of FSS.*

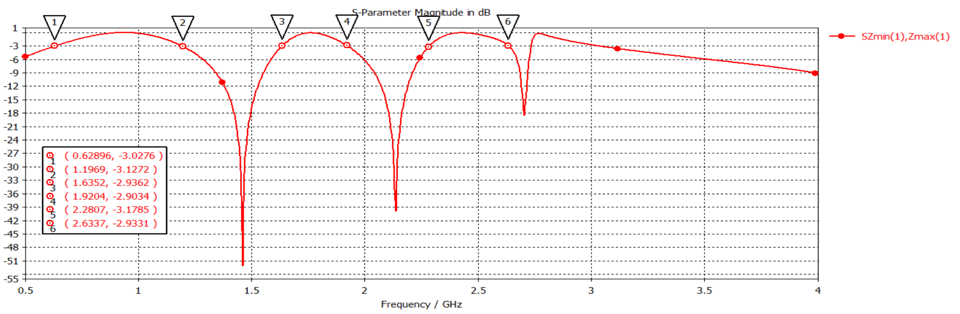


Fig.8 (b) *Simulated Transmission curve at Triple Square of FSS*

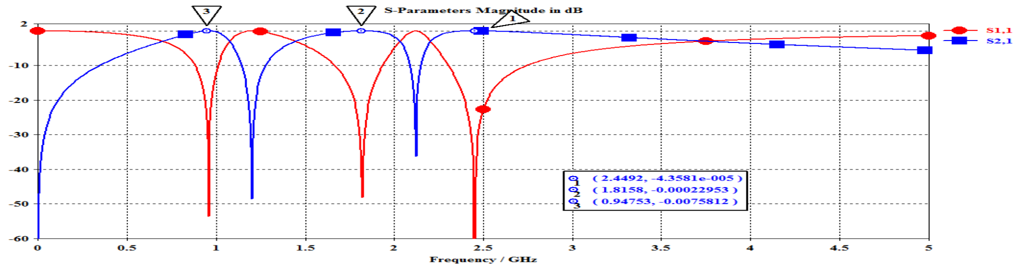


Fig. 8 (c) *Simulated Transmission curve at Triple Square of FSS by equivalent circuit*.

Fig. 8. *Transmission curves at Triple Square of FSS. (a&b) Simulated by CST-microwave studio(c) by equivalent*.

XI. CONCLUATION

For Single Loop FSS, it has the behavior of Band-Stop filter, as shown in Fig. 4 (a,b,c). From the equivalent circuit model. For SSL-FSS with increase w/λ, the resonance frequency shifts to a lower frequency also with increase in the transmission bandwidth .this also applied for Band-Pass filter.

Using Triple Square Loop structure it is shows from simulation it has the property of triple band-pass at 945MHz, 1785MHz and 2.4GHz.

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