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The study of frequency selective surfaces(FSS) periodic structures using metamaterial periodic structures for electromagnetic wave surface modeling

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I dedicate this modest work to the woman who sacrifaced her life to our education my dearest mother “NORA”.

To the man who means the world that encourages me and give me strength to believe my dearest father “ABDELKADER”.

The light of my eyes my parents.

To my dear sister “SOUMIA” and my two brothers “AYOUB” and “AISSA” whom I love very much.

To my dear nephew “DJAMEL ELDDINE”.

To the memory of my paternal and maternal grandmothers and my grandfathers.

To my partner Ikram who shared with me happiness and misfortune as well as all her family.

Without forgetting my dear friends Ilhem, Sabrina, Hiba, Saida andany person who loves me.

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TO THE MEMORY OF MY FATHER

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I pray to God Almighty to bless him with his mercy and to dwell in his vast gardens.

TO My Dear Mother FATIMA EL ZAHRAAsource of tenderness, patience and sacrifice.

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Although I can say and write, I could not express my great affection

and my deep gratitude. I hope never to disappoint you, nor to betray your trust and your sacrifices.

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To all the members of my family, my aunts and my uncles and their children.

To My partner Fatima Zohra who shared with me happiness and misfortune as well as all her family.

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IKRAM

Abstract

Frequency selective surfaces (FSS) are periodic structures that generate a bandpass or a bandstop frequency response. They are used to filter or block RF, microwave, or, in fact, any electromagnetic wave frequency.

The transposition of phononic crystal approach for the electromagnetic wave will very efficient.Using the phononic crystal approach with Bloch boundaries conditions, our purpose is to simulate a user-specified periodic structure chosen from the built-in unit cell types with electromagnetic waves. Starting with an published model working at C band (4.5 GHz) our purpose is to adapt this model to L band (1 GHz and less).The analysis includes the reflection and transmission spectra, the electric field norm on the top surface of the unit cell, and the dB-scaled electric field norm shown on a vertical cut plane in the unit cell domain.Ther used geometry is about ring shape so called “split ring”.

RESUME

Les surfaces sélectives en fréquence (FSS) sont des structures périodiques qui génèrent une réponse en fréquence de type passe-bande ou coupe-bande. Elles sont utilisées pour filtrer ou bloquer les fréquences RF, micro-ondes, ou, en fait, toute fréquence d'onde électromagnétique.

La transposition de l'approche du cristal phononique pour l'onde électromagnétique sera très efficace. En utilisant l'approche du cristal phononique avec des conditions de frontières de Bloch, notre but est de simuler une structure périodique spécifiée par l'utilisateur, choisie parmi les types de cellules unitaires intégrées, avec des ondes électromagnétiques. En partant d'un modèle publié fonctionnant sur la bande C (4,5 GHz), notre objectif est d'adapter ce modèle à la bande L (1 GHz et moins). L'analyse comprend les spectres de réflexion et de transmission, la norme du champ électrique sur la surface supérieure de la cellule unitaire, et la norme du champ électrique en dB sur un plan de coupe vertical dans le domaine de la cellule unitaire. La géométrie utilisée est en forme d'anneau appelé "anneau fendu".

ملخص

الأسطح الانتقائية للتردد (FSS) هي هياكل دورية تولد ممر نطاق أو استجابة تردد توقف النطاق.يتم استخدامها لتصفية أو منع ترددات الموجات الكهرومغناطيسية أو الموجات الكهرومغناطيسية .سيكون تبديل نهج البلورة الصوتية للموجة الكهرومغناطيسية فعالاً للغاية.باستخدام النهج البلوري الصوتي مع شروط حدود Bloch، فإن هدفنا هو محاكاة هيكل دوري محدد من قبل المستخدم يتم اختياره من أنواع خلايا الوحدة المدمجة مع الموجات الكهرومغناطيسية.بدءًا من نموذج منشور يعمل في النطاقC(4.5جيجاهرتز) ، فإن هدفنا هو تكييف هذا النموذج مع النطاقL(1جيجاهرتز وأقل).يشمل التحليل أطياف الانعكاس والإرسال ، ومعيار المجال الكهربائي على السطح العلوي لخلية الوحدة ، وقاعدة المجال الكهربائي المقاسة بالديسيبل الموضحة على مستوى القطع العمودي في مجال خلية الوحدة.الهندسة المستخدمة هناك تدور حول شكل الحلقة يسمى "الحلقة المنقسمة."

LIST OF ABBREVIATIONS

FSS : Frequency Selective Surfaces.

PCBs: Printed Circuit Boards.

MSs: Metasurfaces.

RFID: Radio Frequency Identification.

RCS: Radar Cross Section.

BW: Bandwidth.

EBG: Electromagnetic Band Gap.

FEM: Finite Element Method.

MoM: Method of Moments.

FDTD: Finite Difference Time Domaine.

IEM: Integral Equation Method.

BEM: Boundary Element Method.

DT: Delay Time.

REA: Radar Effective Area.

TEM: Transverse Electromagnetic.

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GENERAL INTRODUCTION

Metasurfacesare broadly named as planar metamaterials with subwavelength thickness and they can be easily fabricated while using lithography and nano-printing techniques. Both metamaterials and metasurfaces are rapidly growing research directions, and with their use, spatially varying EM or optical responses can be achieved at will, with scattering phase, amplitude, and polarization. Through a good selection of materials and design, the ultra-thin structure of MSs can considerably suppress the detrimental and undesirable losses in the wave propagation direction. When considering the polarization response, all metasurfaces can be categorized based on the operating principle of array element, i-e their functionalities (frequency selective surfaces (FSS), high impedance surfaces, perfect absorbers, reflecting surfaces, etc.). According to the definition in [1], FSSs are metasurfaces that merely exhibit an electric response [2,3]. Since, in order to tailor the frequency selectiveness in transmission/reflection characteristics, only electrical polarization may be sufficient. From the theory of antenna and microwave engineering, these surfaces are made by planar and periodic arrays of metallic patches or strips with different shapes. The patch is of negligible thickness as compared to the wavelength, although it is larger enough in contrast to the metal's skin depth. Consequently, such a structure can impeccably be estimated as a minuscule thin array of perfect conducting resonant elements. This approximation is also applicable to the complementary FSS's structures i-e apertures. However, aperture-type FSS's face a limitation when the area of the cavity/aperture becomes equal to the unit cell (a wire-mesh type) [2,3]. Square and hexagonal wire-mesh unit cells have typically been used and are also termed as the capacitive grid. The existence of the resonating size of array element causes the emergence of the side lobes in the transmitted and reflected fields, which are the defining feature of FSSs. However, as compared to the FSSs, the resonating element and unit cell of metasurface is relatively much smaller than the wavelength and it helps to eliminate the grating lobes in the frequency response. Therefore, FSSs in the terahertz domain are usually termed as metasurfaces [4]. Frequency selective surface (FSS) is a robustly studied topic of electromagnetic (EM) science, which are two-dimensional periodic structures having planar metallic array elements (patch or apertures) on a dielectric substrate, exhibiting transmission and reflection at certain resonant frequency [2]. Depending on the array element design, an incoming plane wave will be either transmitted or reflected, completely or partially. This happens when the frequency of the plane wave matches the resonance frequency of the FSS elements. Therefore, an FSS can pass or block the EM waves with certain frequencies in free space; so they are best identified as spatial filters. Traditionally, the element size, shape, and periodicity of an FSS result in the resonance. FSSs have extensively been investigated over six decades and a range of microwave and optical FSSs structures have been evolved. In past, they were frequently used in reflector antennas [5], including diplexers for quasi-optical microwave devices, resonant beam splitters, and antenna radomes [6,7]. Nowadays, FSSs have been employed in dichroic sub-reflectors [8], radio frequency identification (RFID) [9], lenses antennas [10], and protection from electromagnetic interference [11]. Currently, the most famous applications of FSSs are as antennas radomes and controlling radar cross-section (RCS). Their performance is limited by the design complications, including the requirement of compact size and insensitivity to the incidence angle, as well as polarization of EM wave, consequently stipulating to improve their design features.

Traditional FSSs are narrow band and they do not provide adequate spatial filtering response. Extensive research is going on to miniaturize the FSSs and improve the frequency response with broader bandwidth (BW) at higher incidence angles and dual polarization. However, single layered FSS structures have been proved inefficient due to unstable performance with the variation of EM wave incident angle. To overcome the limitations of conventional single layer FSSs, multilayered FSSs have been introduced, which offer additional flexibility of varying parameters for desired performance [12,13]. At present, FSSs based on fractal elements and miniaturized arrays (2.5 dimensional) are employed for compactness [14,15]. Three-dimensional FSS structures and active FSSs have opened new doors in microwave technology [16,17]. Additionally, embedded FSS (with inserted metallic rods and plates based on stepped-impedance resonator) [18], integrated FSS and Electromagnetic band gap structures (EBG) [19], and metamaterialFSSs are the most recent advances implemented by microwave researchers. In the past, dispersion properties of FSSs have been explored through approximate analytical techniques, for example, which involve equivalent circuit method to analyze the transmission line characteristics (By Quasi-static approximation). However, with the growth of more complex structures, state-of-the-art numerical methods have been introduced, which use periodic boundary conditions (PBC) allowing for the design analysis quite straightforward. Some of these include finite element method (FEM), method of moments (MoM), finite difference time domain method (FDTD), and the integral equation (boundary element) method (IEM/BEM) . A well-known technique is IEM/BEM used in combination with the MoM[20]. Various designs of FSSs and schemes to examine their EM characteristics are well presented in [2,3].

CHAPTER1 : TRANSMISSION LINE THEORY

1.1. Introduction

-Transmission line: a bridge between circuit theory and electromagnetic theory.

-By modeling transmission lines in the form of equivalent circuits, we can use Kirchhoff's Voltage and Current laws to develop wave equations whose solutions provide an understanding of wave propagation, standing waves, and power transfer.

-Fundamentally, a transmission line is a two- port network, with each port consisting of two terminals. One of the ports, the line's sending end, is connected to a source (also called the generator). The other port, the line's receiving end, is connected to a load as shown in the following figure(1.1)[21].

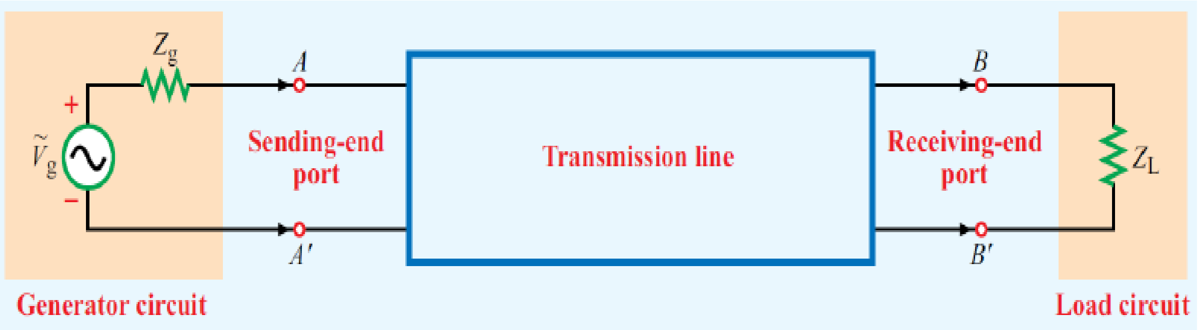


Figure 1. 1 : equivalent circuit of transmission lines

1.2. Definition of transmission line

Transmission lines are used to carry electromagnetic energy from one point to another. It means it transfer from one point to another. Generally it consists of two conductors. It is used to connect a source to a load. The source may be a transmitter or an electric generator and the load may be an antenna. Transmission lines are used for operational frequencies equal to or less than about 3GHz. above 3GHz they will be replaced by waveguides.

Transmission lines are commonly used in power systems for power transmission. These lines can be used as circuit elements like capacitors, inductors at ultra high frequencies (300-3000MHz)[22].

1.3. Transmission lines parameters

Capacitance per-unit-length C (F/m).

Inductance per-unit- length L (H/m) .

Characteristic impedance Z_0 (Ω).

Velocity of propagation vp (m /s).

Per-unit-length delay time tp = $1/v_p$ (s/m).

Delay time (DT) $t_d = l/v_p = lt_p$ (sec).

1.3.1. Transmission lines Equations

- **Lossless transmission lines:**

$$-[V(z+\Delta z)-V(z,t)] = L.\Delta z\frac{\partial i(z,t)}{\partial t} \qquad (1.1)$$

$$-[i(z+\Delta z,t-i(z,t)] = c.\Delta z\frac{\partial V(z+\Delta z,t)}{\partial t} \qquad (1.2)$$

After taking Δz → 0

- **Telegrapher’s Equations:**

$$-\frac{\partial v(z,t)}{\partial z} = L\frac{\partial i(z,t)}{\partial t} \qquad (1.3)$$

$$-\frac{\partial i(z,t)}{\partial t} = c\frac{\partial v(z,t)}{\partial t} \qquad (1.4)$$

- **Wave Equation:**

$$-\frac{\partial v(z,t)}{\partial z} = L\frac{\partial i(z,t)}{\partial t} \qquad (1.5)$$

$$-\frac{\partial i(z,t)}{\partial t} = c\frac{\partial v(z,t)}{\partial t} \qquad (1.6)$$

Wave equation:

$$\frac{\partial^2 v(z,t)}{\partial z^2} = Lc\frac{\partial^2 v(z,t)}{\partial t^2} = 1/V_p^2\frac{\partial^2 v(z,t)}{\partial t^2} \quad (1.7)$$

$$\frac{\partial^2 i(Z,t)}{\partial Z^2} = Lc\frac{\partial^2 i(Z,t)}{\partial t^2} = 1/V_p^2 \quad (1.8)$$

- **General wave Solutions**

$$\frac{\partial^2 v}{\partial Z^2} = LC\frac{\partial^2 v}{\partial t^2} = 1/V_p^2\frac{\partial^2 v}{\partial t^2} \quad (1.9)$$

- **General solution for voltage**

$$V(Z,t) = V^+(Z - V_p t) + V^-(Z, V_p t) \quad (1.10)$$

$$= V^+(t - Z/V_p) + V^-(t + Z/V_p)$$

$$\begin{cases} (t - z/v_p) = +Z \text{ direction} \\ (t + z/v_p) = -Z \text{ directio} \end{cases}$$

- **Velocity of propagation**

$V_p = \frac{1}{\sqrt{LC}}$ (m/s) (1.11)

- **General solution for current**

$i(z,t) = i^+(t - z/v_p) + i^-(t + z/v_p)$ (1.12)

$$-\frac{\partial V(Z,t)}{\partial Z} = L\frac{\partial i(Z,t)}{\partial t} \quad (1.13)$$

$$-\frac{\partial i(Z,t)}{\partial t} = c\frac{\partial V(Z,t)}{\partial t} \quad (1.14)$$

$$\frac{1}{Vp}\left\{v^+(t - z/v_p) - v^-(t + z/v_p)\right\} = L\left\{i^+\left(t - \frac{z}{Vp}\right) + i^-(t + \frac{z}{Vp})\right\} \quad (1.15)$$

$$\frac{1}{Vp}\left\{i^+\left(t - \frac{z}{V_p}\right) + i^-(t + \frac{z}{V_p})\right\} = C\left\{v^+(t - z/v_p) - v^-(t + \frac{z}{v_p})\right\} \quad (1.16)$$

$$\mathrm{i}(\mathrm{z},\mathrm{t}) = \frac{\mathrm{v}^{+}\,(\mathrm{t}-\mathrm{z}/\mathrm{v}_{\mathrm{p}})}{Z_0} - \frac{\mathrm{v}^{-}\,(\mathrm{t}+\mathrm{z}/\mathrm{v}_{\mathrm{p}})}{Z_0} \tag{1.17}$$

- **CharacteristicImpedande :**

$$Z_0 = v_p L = \frac{1}{vpc} = \sqrt{\frac{L}{C}} \tag{1.18}$$

1.4. Propagation speeds for Typical Dielectric

the table 1.1 allowing comparison among different dielectric materials to propagation speed for typical dielectric

Table 1. 1 : propagation speeds for typical dielectric.

Dielectric	Rel-Dielectric constant εr	Propagation speed cm/nsec	Dely time per unit length (ps/cm)
polymide	2.5 – 3.5	16 - 19	53 - 62
Silicon dioxide	3.9	15	66
Epoxy glass (PCB)	5.0	13	75
Alumina (ceramic)	9.5	10	103

1.5 Lumped-element model

- A transmission line can be represented by a parallel wire configuration, regardless of its specific shape or constitutive parameters.
- To obtain equations relating voltages and currents, the line is subdivided into small differential sections[23].

1.5.1Transmission lines for lumped model

Consider the equivalent circuit of a two-conductor transmission model of differential length Δz shown in (figure 1.2).

i (z,t) and v(z,t) denote the instantaneous current and voltage at a specific segment of the transmission line (specitial and Temporal variation).

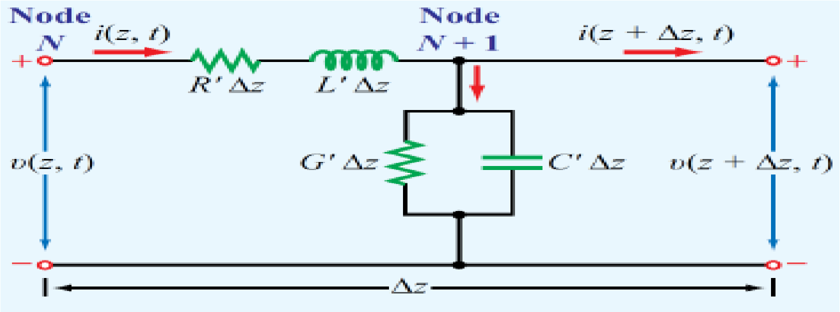


Figure 1. 2 : Equivalent circuit of a two – conductor transmission line of differential length Δz .

- **Kirchhoff's voltage law :**

$$V(z, t) - R'\Delta z\ i(z, t) - L'\Delta z \frac{\partial i(z,t)}{\partial t} - v\ (z+\Delta z\ ,t) = 0 \qquad (1.19)$$

- **Kirchhoff's current law :**

$$i(z\ ,t\ ) - G'\Delta z\ v(\ z+\ \Delta z\ ,t) - C'\ \Delta z \frac{\partial v(z+\Delta z,t)}{\partial t} - i(z+\Delta z,t) = 0 \qquad (1.20)$$

- **Telegrapher's Equations :**

$$-\frac{\partial v(z,t)}{\partial z} = R'\ i(z,t) + L'\frac{\partial i(z,t)}{\partial t} \qquad (1.21)$$

$$-\frac{\partial i(z,t)}{\partial z} = G'\ v(z,t) + C'\ \frac{\partial v(z,t)}{\partial t} \qquad (1.22)$$

- **Telegraphe's equation in phasor form :**

$$-\frac{d\tilde{v}(z)}{dz} = (R' + J\omega L')\tilde{I}(z) \qquad (1.23)$$

$$-\frac{d\tilde{I}(z)}{dz} = (G' + j\omega C')\ \tilde{v}(z) \qquad (1.24)$$

- **Voltage – current relationship:**

$$\tilde{I}(z) = I^{+}e^{-\gamma z} + I^{-}e^{+\gamma z} = -\frac{1}{R'+j\omega L'}\frac{d\tilde{v}(z)}{dz} = \frac{\gamma}{(R'+j\omega L')}\ [V^{+}e^{-\gamma z} - V^{-}e^{+\gamma z}] \qquad (1.25)$$

$$= \frac{V^{+}{}_{0}}{z}\ e^{-\gamma z} - \frac{V^{-}{}_{0}}{z}\ e^{+\gamma z}$$

Where $\frac{V^{+}_{0}}{I^{+}_{0}} e^{-\gamma z} + z_0 = \frac{V^{-}_{0}}{I^{-}_{0}}$

- **Characteristic Impedance of the line**

$$Z_0 = \frac{R' + j\omega L'}{\gamma} = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}} \qquad \text{Unit: Ohm} \qquad (1.26)$$

- **Propagation constant for lossless line**

$$\gamma = \alpha + j\beta \approx \sqrt{(j\omega L')(j\omega C')} = j\omega\sqrt{L'C'} \quad (1.27)$$

1.6. Planar transmission lines

Planar transmission lines are the most essential point MICS circuits, mainly due to their properties[24]:

- Low cost, low weight, small sizeand light weight.
- Compatibility with integrated circuits.
- Good performance.
- Better reliability.
- Reproducibility.

The first work on planar microwave transmission lines was done in 1952, when Greig and Engleman first proposed the microstrip line, which was used as a substrate for non-planar waveguides and coaxial cables. In the late1960’s two other types of planar transmission lines were also invented, namely slotted and coplanar lines. These two configurations use only one side of the substrate. In the seventies, in order to overcome the disadvantages of the microstrip line due to the presence of higher modes and spurious couplings, a class of structures combining a planar and a non- planar geometry, such as shielded suspension lines or finned lines was proposed[25].

1.6.1. The microstrip line

The microstrip line consists of dielectric substrate metalized over its entire width on the lower side and coverd with a narrow metal strip on the upper side. The geometry of a microstrip line is illustrate in (Figure1.3).

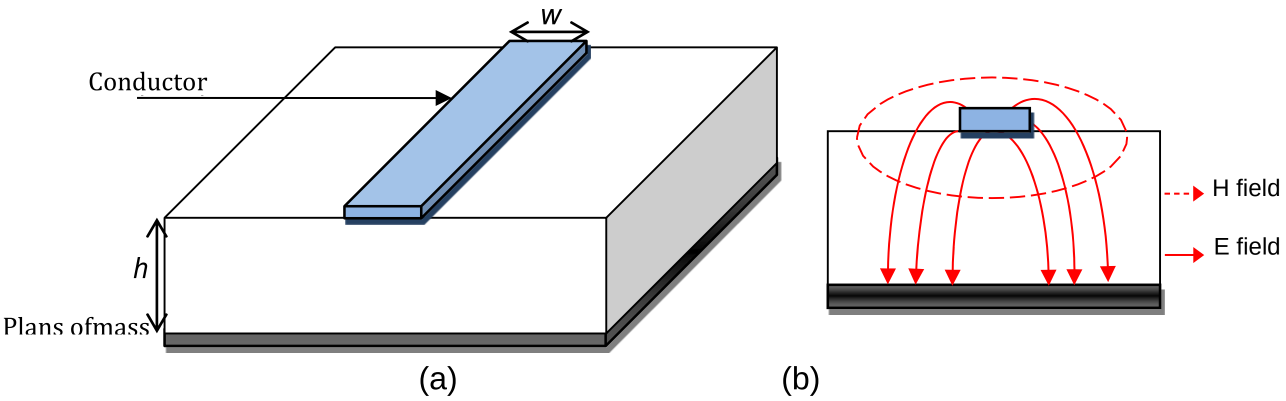


Figure 1. 3 : (a) Toplogy of microstrip line (b)Distribution of electric and magnetic [26].

The electromagnetic field lines of the microstrip line are located mainly in the dielectric substrate and fraction of the field in the air. The propagation mode is not TEM because the medium is not homogenous, however the amplitudes of the longitudinal component of the electric and magnetic fields are small enough to be neglected, so the mode is said to be quasi TEM.

The main parameters that characterize the microstrip structure are:

The permittivity ε_r(often chosen high to concentrate the electromagnetic field and thus reduce radiation losses), and the geometric parameters w and h (typically $0.1 \leq \frac{w}{h} \leq 10$ [27].

The microstrip line is the most used among all planar structures because of its simplicity, ease of fabrication and integration into microwave devices.

Nevertheless, it has some disadvantages such as in the case of parallel connection, the realization of short circuit by returning to the mass must be done with the help metalized holes. The latter generate parasitic effects.

The second disadvantage this technololgy is that the range of achievable characteristic impedances is restricted once the substrate characteristics are chosen since there is only one value of width w of the microstrip line for corresponding impedance value[27].

1.6.2. Coplanar line

The coplanar toplogy consists of two ground planes and a central strip located on the same side of the substrate Figure(1.4a). In this type of technology two modes can be exited continuously due to the presence of three conductors: an even mode and an odd mode. Figure1.4b shows the distribution of the electric and magnetic fields in the coplanar line topology.

Thanks to this configuration, the coplanar line has many advantages: the elimination of the associated parasitic effects, the possibility off realizing a characteristic impedance with different line dimensions, the ease of transferring components in parallel or in series.

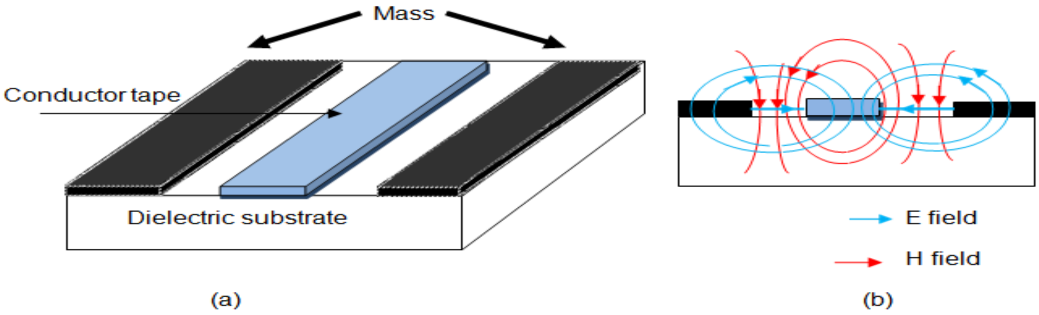


Figure 1. 4 : (a) Toplogy of microstrip line (b)Distribution of electric and magnetic [26].

However, the presence of two modes is one of the main drawbacks of this technology, and the lack of reliable models in the library of common circuit.

simulation software makes the use of coplanar technology difficult from a design perspective[28].

1.6.3. The slotted line

The slit line is illustrated in figure(1.5). The electric field lines run through the slit and the magnetic field lines run around the conductors. If the widths of the two strips are equal, the configuration is symmetrical, if they are different the configuration is asymmetrical.

The advantage of this method compared to the microstrip line is that the insertion of the series and parallel components is done without having to use the plated holes that introduce of parasitic elements. In addition, a sltted line occupies less surface area than a coplanar line, which leads to lower manufacturing costs[24,28].

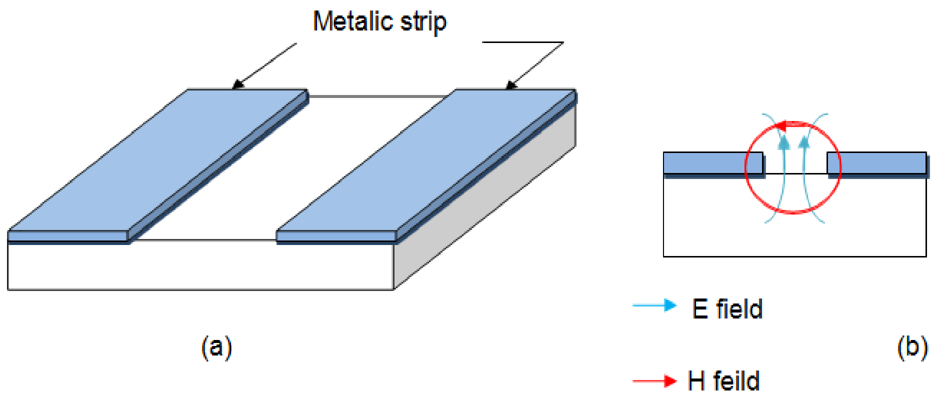


Figure 1. 5 : (a) Toplogy of slit line (b)Distribution of electric and magnetic [26].

1.6.4. Triplate line

The triplate technology consists in using a metal strip embedded in a substrate. On the two lower and upper sides, ground planes are located. There are several forms of triplate lines such as the centered or symmetrical line(the transmission line is located at equal distance from the two ground planes), the decentered or asymmetrical line(the strip is closer to one of the two ground planes) as we can see in the figure (1.6).

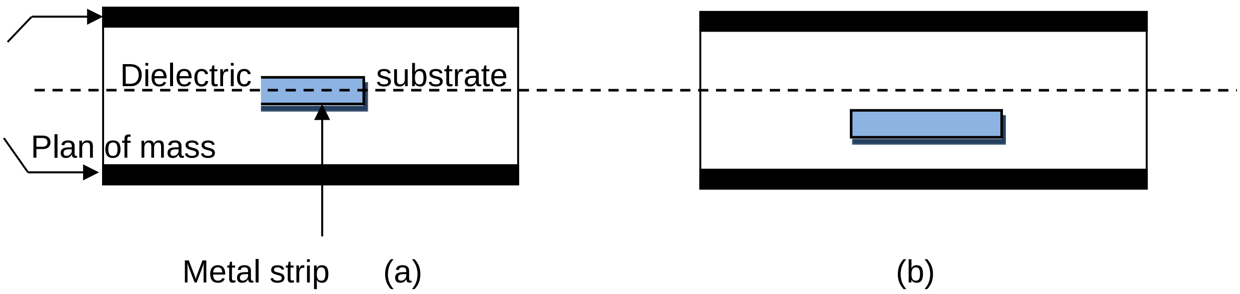


Figure 1. 6 : (a) Toplogy of triplate line. (b)Distribution of electric and magnetic [26].

As in the case of coplanar technology, the presence of three conductors leads to the existence of two different modes, however only one is exploitable. The triplate circuits are well isolated from electromagnetic interference and there are no radiation losses.

The major disadvantages of this technology are the technological dispersions which have a strong impact on the electrical response because of the total immersion of the line in the substrate. Moreover, the transfer of active elements or any other discrete element is not easy[25].

1.7. Multilayer technology

In order to satisfy the criteria of low cost, small size of circuits and interconnections, and the need to increase the frequency of communication systems, multi-level or multilayer integration solutions have been developed. This technology comprises several dielectric layers with different permittivities and different levels of mittalizationwich are coupled by electromagnetic field or directly connected to each other through mettalized holes, figure(1.7)[24].

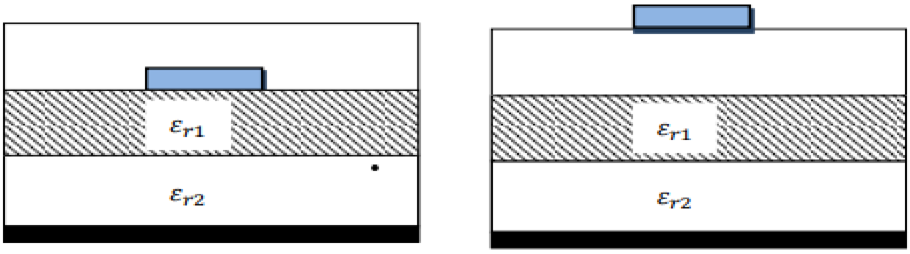


Figure 1. 7 : Multilayer topology [26].

This technology offers several advantages:

It is possible to realize partially coupled lines on two different metallization levels in order to reach high coupling levels[24,25]. The possibility of using the different layers as a support for the different elements increases the compactness of the systems and their efficiencies as well as the possibility of obtaining very high or very low impedance values.

The main disadvantage of this technology is the complexity of the technological process campared to conventional planar technologies[24].

Undoubtedly, among these different planar topologies, the microstrip line is the most used. In the following section, a detailed study of the microstrip resonator will be carried out.

1.8.Microstrip resonators

1.8.1.General characteristics of a microstrip resonator

The characteristics of a microstrip line, such as the characteristic impedance $Z_c$and the effective dielectric constant ε_{eff}, all depend on its geometry and the relative dielectric constant ε_r of the substrate.

- **Dielectric Permittivity**

The microstrip line is an inhomogeneous propagation medium, consisting of two different dielectric media (air and substrate). This discontinuity of the propagation media makes it difficult to study and analyze the structures. A technical solution to this electromagnetic problem consists in introducing a new quantity called effective permittivity. The idea is to immerse the line in homogeneous and isotropic intermediate dielectric medium, with permittivityε_{reff} given by[29].

$$\text{Pour } \frac{W}{h} \le 1: \varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\left(1+\frac{12}{W/h}\right)^{-\frac{1}{2}} + 0.04\left(1-\frac{W}{h}\right)^2\right] \tag{1.28}$$

$$\text{Pour}\frac{W}{h} > 1:\ \varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12}{W/h}\right)^{-\frac{1}{2}} \tag{1.29}$$

- **Characteristicimpedance :**

The expressions of the characteristic impedance of a microstrip line depend on its characteristics : length (L), width (W), height (h) and the effective permittivity of the dielectric ε_{reff}, they are given by the following approximate formulas[29].

$$\text{Pour}\frac{W}{h} \le 1:\ Z_C = \frac{60}{\sqrt{\varepsilon_{eff}}}\ln\left(\frac{8h}{W_{eff}} + \frac{W_{eff}}{4h}\right) \tag{1.30}$$

$$\text{Pour}\frac{W}{h} > 1: Z_C = \frac{120\pi}{\sqrt{\varepsilon_{eff}}}\ln\left(W_{eff} + 1.393 + 0.667 * \ln\left[\frac{W_{eff}}{h} + 1.444\right]\right) \tag{1.31}$$

$W_{eff}$is the equivalent width of the tape(W) given by the following expressions:

$$\text{Pour}\frac{W}{h} \le \frac{1}{2\pi}: \frac{W_{eff}}{h} = \frac{W}{4h} + \frac{1.25t/h}{\pi}\left(1 + \ln\left(4\pi\frac{W/h}{t/h}\right)\right) \tag{1.32}$$

$$\text{Pour}\frac{W}{h} > \frac{1}{2\pi}: \frac{W_{eff}}{h} = \frac{W}{4h} + \frac{1.25t/h}{\pi}\left(1 + \ln\left(\frac{2}{t/h}\right)\right) \tag{1.33}$$

Since wave propagation in a microstrip line takes place in both the dielectric medium and the air Figure, the distribution of field lines that extend around and into the structure depends primarily on:

- Of the width W of the metallization circuits.
- Of the characteristics of the substrate namely its dielectric constant $\varepsilon_r$and its thichness h.

Losses in microstrip resonators:

One of the main limitations of microstrip resonators are the insertion losses which result in a low quality factor, this presents a serious handicap in the design of highly selective filters in planar technology.

The losses present in resonators can be of dielectric, metallic and radiation origin[30,31].

a. Metallic losses

These losses are the main source of losses in a conventional planar circuit.They are due to the metallic conductors (ribbon and ground plane) which have a finite conductivity, so they will inevitably have a resistivity different from zero, therefore when the wave passes, there will be heating of the conductors and heat dissipation by Joule effect.

b. Dielectric losses

In general, the dielectric losses of a microstrip line are much lower than the metallic losses. They are caused by the fact that the substrate (dielectric) used is not perfectly insulating.

c. Radiation losses

They are due to the geometry of the resonators, to the discontinuities, and to the surface condition of the metallization, as well as to the characteristics of the substrate, and they are directly related to the frequency since they increase with the increase of this one.

In some cases and to eliminate radiation losses, it is preferable to shield the circuit by surrounding it with a metal enclosure[29].

The choice of the values of these parameters generally conditions the type of application to be designed withmicrostrip technology. For the realization of microwave circuits, the free space radiation of the line will be minimized, consequently the choice of the substrate will be such that the electromagnetic energy remains concentrated in the dielectric, so the substrate will have a high dielectric constant. For antennas, the most suitable substrate is one with a low dielectric constant, a large thickness (relative to the operating wavelength) and low losses ($tang\delta$). A thick substrate increases the power radiation by the antennas, reduces the Joule losses and improves the bandwidth of the antennas, in return the weight is increased[32,33].

1.9 CONCLUSION

Transmission lines are used for purposes such as connecting radio transmitters and receivers with their antennas (they are then called feed lines or feeders), distributing cable television signals, trunklines routing calls between telephone switching centres, computer network connections and high speed computer data buses. RF engineers commonly use short pieces of transmission line, usually in the form of printed planar transmission lines, arranged in certain patterns to build circuits such as filters. These circuits, known as distributed-element circuits, are an alternative to traditional circuits using discrete capacitors and inductors[22].

CHAPTER2 : FREQUENCY SELECTIVE SURFACES AS SPATIAL FILTER

2.1 Definition of FequencySelectives Surfaces

Frequency Selective surfaces(FSS), are periodic structures with metallic or dielectric patterns that, as their names suggest perform a filtering operation.These structures are a key element in the design of systems with multiple resonant frequencies[34,35].

FSS with metallic patterns printed on dielectric substrate are used as bandpass filters. These structures can also be designed to give the spectral responses of high-pass and low-pass filters.

2.1.1 Operating theory of FSS

FSS structures(capacitiveb and inductive), also also called spatial filters, are analogous to the microwave filters according to the circuittheory. Filtering characteristics of FSS can be categorized into the four kinds, including low pass, high pass, stop band, and passband. Low pass FSS filters permit a lower range of frequencies to pass through the structure, while by pass higher range of frequencies. High pass FSS filter operation is a counterpart of low pass filter function by applying Babinet principle. Similarystopband FSS filter blocks undesired frequencies while passband filter allows only specific frequency range. For a desired resonant operation. FSSs are designed by periodic arrays of metal patches and/or slots etched on a dielectric material. Theappropriate selection of FSSs array elements, shape, dimension, and substrate material is the most important part of the design process.

The operational theory of FSS based structures has been explained by Munk in detail[36]. Figure(2.1) shows the functionality of FSS achieved by a complementary self-resonating network. Simply, when EM waves are incident on FSS structure, they incite electric currents into the array elements. The level of coupling energy defines the amplitude of the produced currents. However, these generated currents also work as EM sources and they create additional scatterd fields. Incident EM fields combined with these scatterd fields make up the resultant field in the surrounding of FSS. Consequently, the required currents and field characteristics can be obtained by properly designed elements and create the filter response.

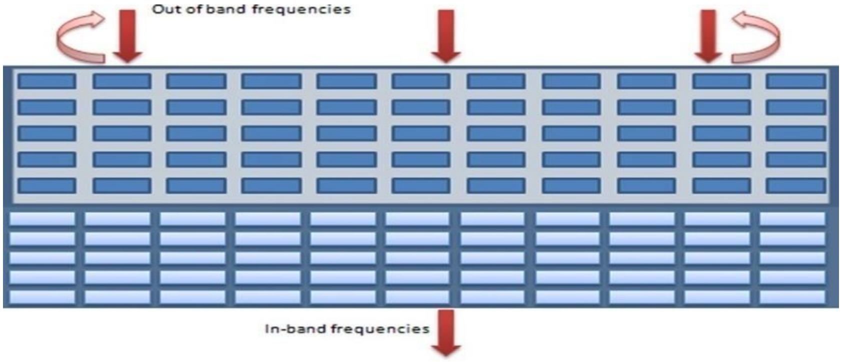


Figure 2. 1 : Functional description of FSS [37, 38, 39].

2.1.2 Periodic Structures

When identical unit cell formed by one, two or more materials with different properties are arrangedand in an infinite array of one or two-dimensions, a periodic surface is formed[36]. Two basic means to excite a periodic array are known: one is through an incident plane wave (a passive array type) or by the attached generators to individual element (an active array type). In the former type, the incoming plane wave (E_i) will partically be transmitted (E_t) in the forward direction and in part reflects (E_r) speculary. In the condition of resonance and without grating lobes, the amplitude of the reflected wave E_r may be equal to incident wave E_i, while the transmitted signal E_t is equal to zero. The specular reflection coefficient (Γ) can be defined by equation(2.1).

$$\Gamma = {}^{E_r}/_{E_i} \tag{2.1}$$

Similarly, the transmission coefficient(T) can be defined by equation (2.2)

$$T = {}^{E_t}/_{E_i} \tag{2.2}$$

The FSS can be excited by a normal plane wave (in the –z direction) or an oblique wave as shown in figure (2.2).

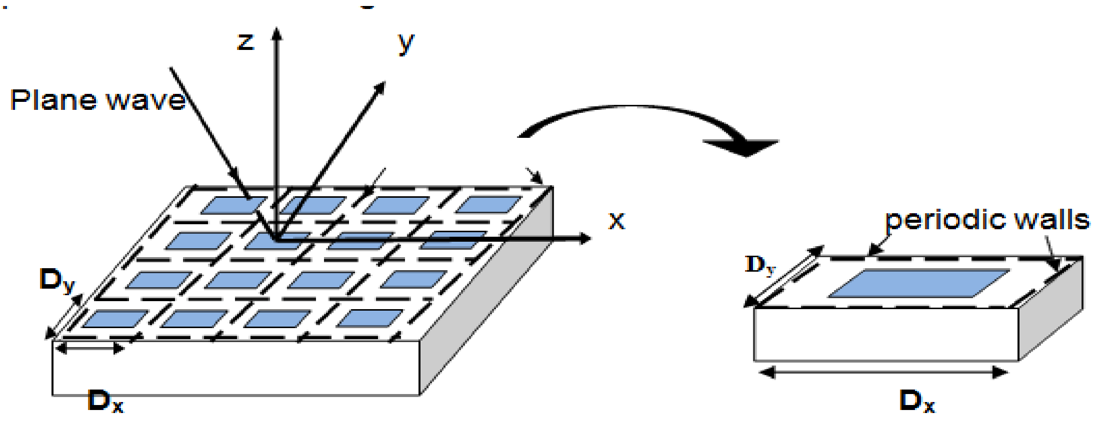


Figure 2. 2 : periodic structure and its unit cell[26].

2.1.3 Wave propagation in periodic structure

When a periodic structure FSS is excited by a plane wave of length λ, a part of the incident wave will be transmitted while the other part will be reflected with a certain phase shift. This is determined by the geometry of the periodized patterns, their dispersion properties…The resonance phenomenon appears when the size of the periodic lattice elements is a multiple of $\lambda$the excitation wavelength[40,41]. In general the performance and behavior of an FSS is influenced by the following factors[42,43]:

- The conductivity of the conductor.
- The geometry of the elements.
- The permittivity of the substrate: by increasing the permittivity of the substrate the resonance frequency decreases.
- The thickness of the substrate, which directly influences the resonance frequency up to a value of a few millimeter.
- The periodicity of the network which mainly affects the width of the bandwidth, when the period increases the width of the band decreases.
- The distance between the different layers, in the case of a multilayer structure.
- The number of layers in the case of a multilayer structure.
- The number of periods (determine the number of periods for which the FSS ceases to behave as a periodic structure).

2.1.4Fequency response of an FSS

After the passage of the electromagnetic wave through the FSS some frequencies will be transmitted while others will be reflected. As mentioned in the previous section, the response of an FSS to an excitation depends on several factors, among which the geometry and the type of patterns. From these patterns and their geometries, an FSS can be designed to produce the four spectral responses: bandcutter, bandpass, lowpass and highpass, as illustrated in figure(2.3). Of course, design criteria such as attenuation level, cutoff frequency, bandwidth, and wave incidence angle also influence the type of frequency response[35].

- **Bandwidth:**

In the design of a broadband FSS, the bandwidth of the element is very important. To increase the bandwidth of the FSS, it is important to try to arrange the elements closer together, choosing elements that minimize the cell size[34]. The bandwidth of a notch or bandpass FSS can also be extended by placing two FSS in parallel(double screen FSS) and choosing the distance between the two surfaces carefully.

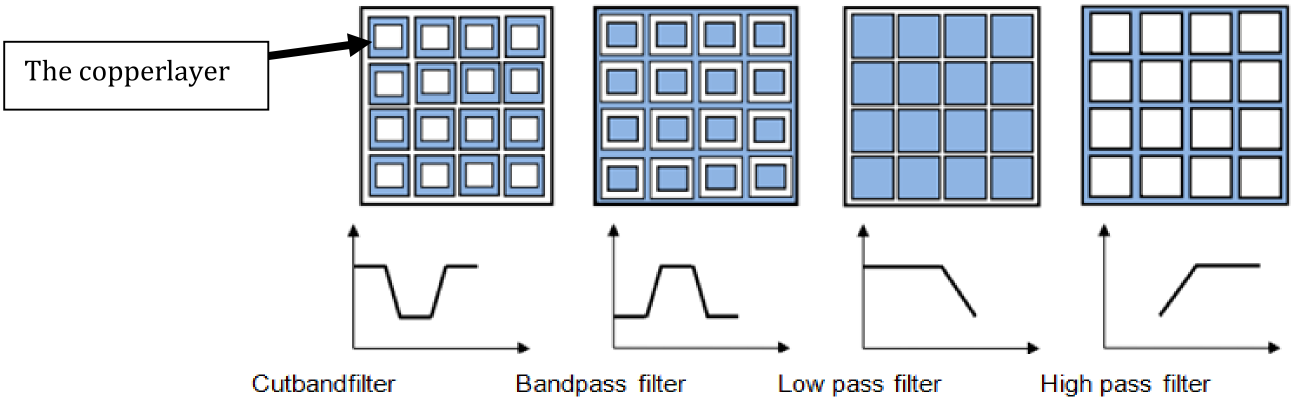


Figure 2. 3 : Different types of frequency responses of an FSS[26].

2.2Types of FSS

Here, in this section, we categorize the FSS on the basis of array element, structure design,andapplication. Figure(2.4) gives the basic geometries of the FSS.

2.2.1 FSS Based on Array Elements

We cover three types of FSS based on array elements, including basic element type FSS, convoluted/meandered FSSs, and fractal FSS.

2.2.1.1 Basic Element Type FSSs

In general, four basic type of FSS element groups have been classified[36] and are illustrated in figure(2.4)and figure(2.5). This includes GroupA(centrally connected or N-poles, such as dipole, tripole, square-spiral, Jerusalem crosses), GroupB(looped shapes, e.g. circular, square, hexagonal loops), GroupC(solid interiors or patch shapes of different shapes), and GroupD(combinations of above all). Depending on the potential application, FSS designers select array element from any of these groups and/or use a combination of these as well. A good element should present a stable resonance response with the variation in incidence angles. Commonly, selecting a groupB element with a larger loop area is beneficial and it enhances the bandwidth[36].

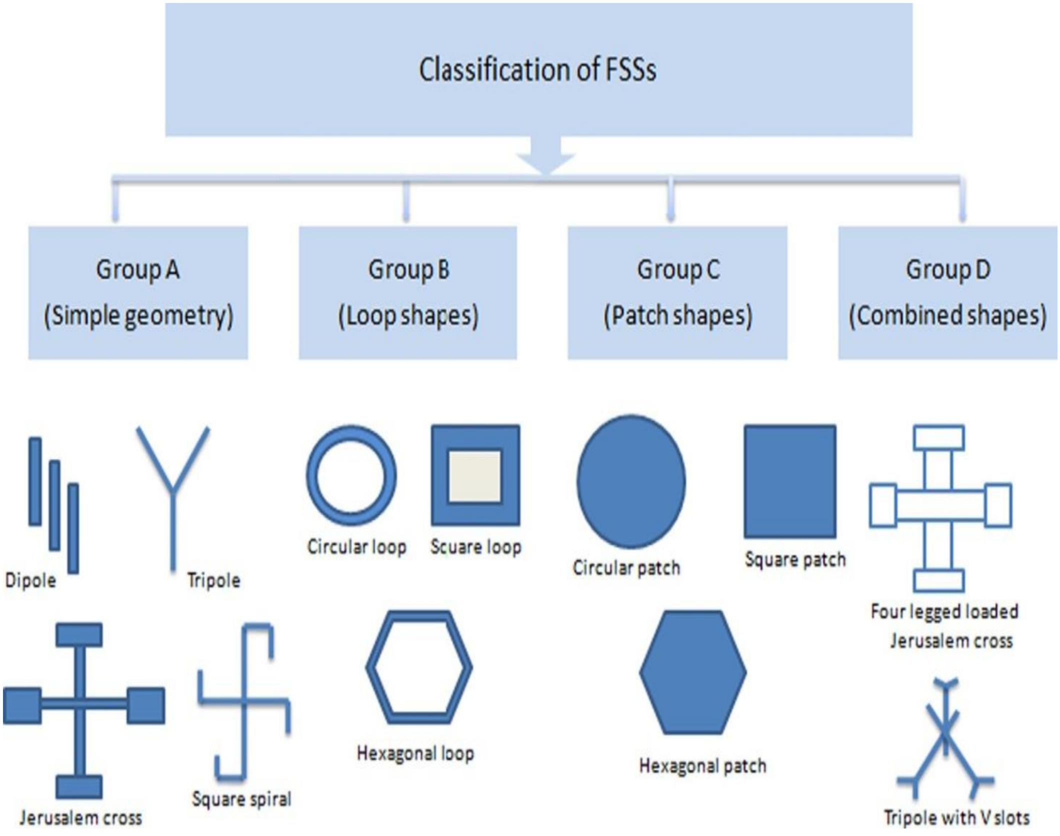


Figure 2. 4 : Grouping of basic geometries of FSS [37, 38, 39].

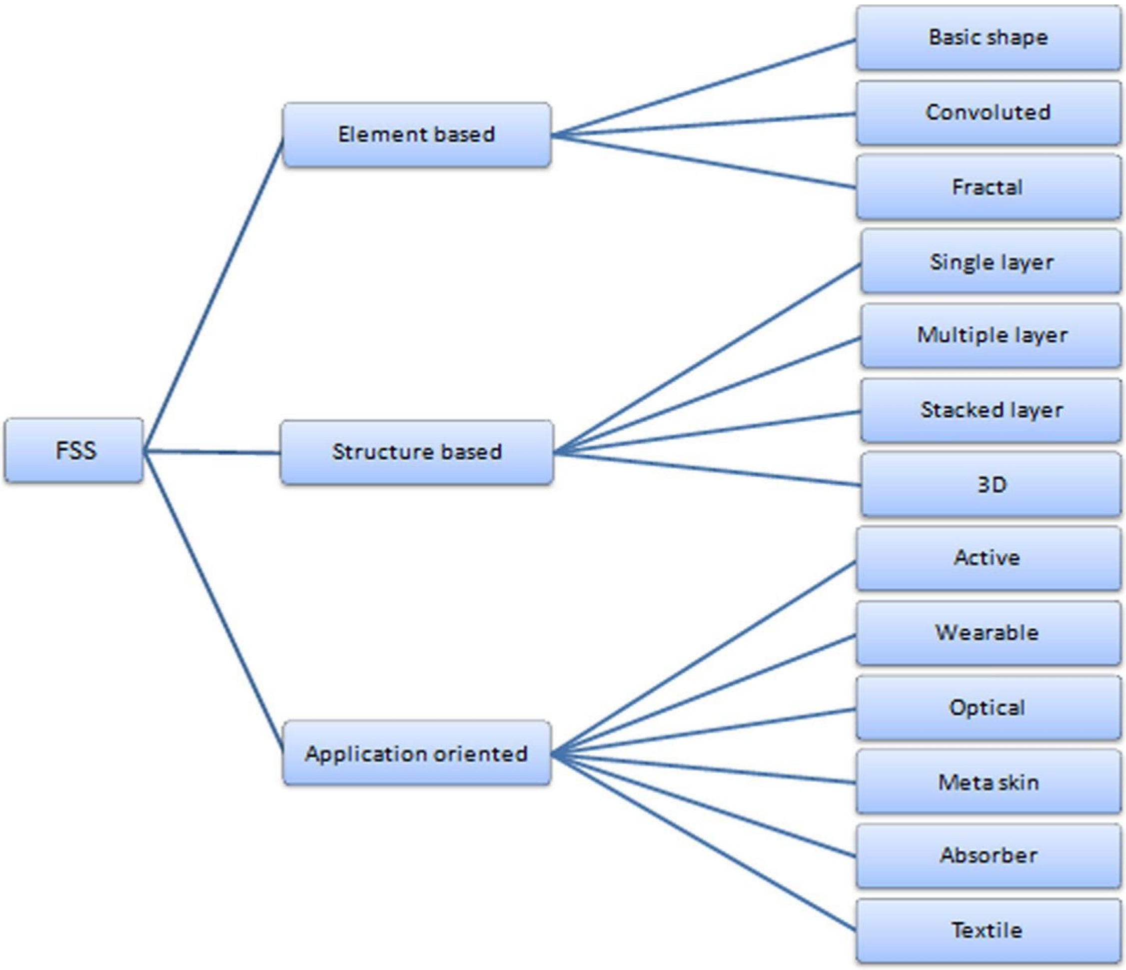


Figure 2. 5 : Classification of FSS [37, 38, 39].

2.2.1.2Convoluted or Meandered FSS

Some applications demand miniaturized FSS, especially in radomes where flexibility is a challenge for FSS designers, FSS's with relatively small electrical dimensions are enviable, so that the unit cell size is reduced without affecting the angular stability. It is proved in [44] that the convoluted square loop FSS structures can present better stability in polarization as compared to the simple element as shown in the following figure (2.6).

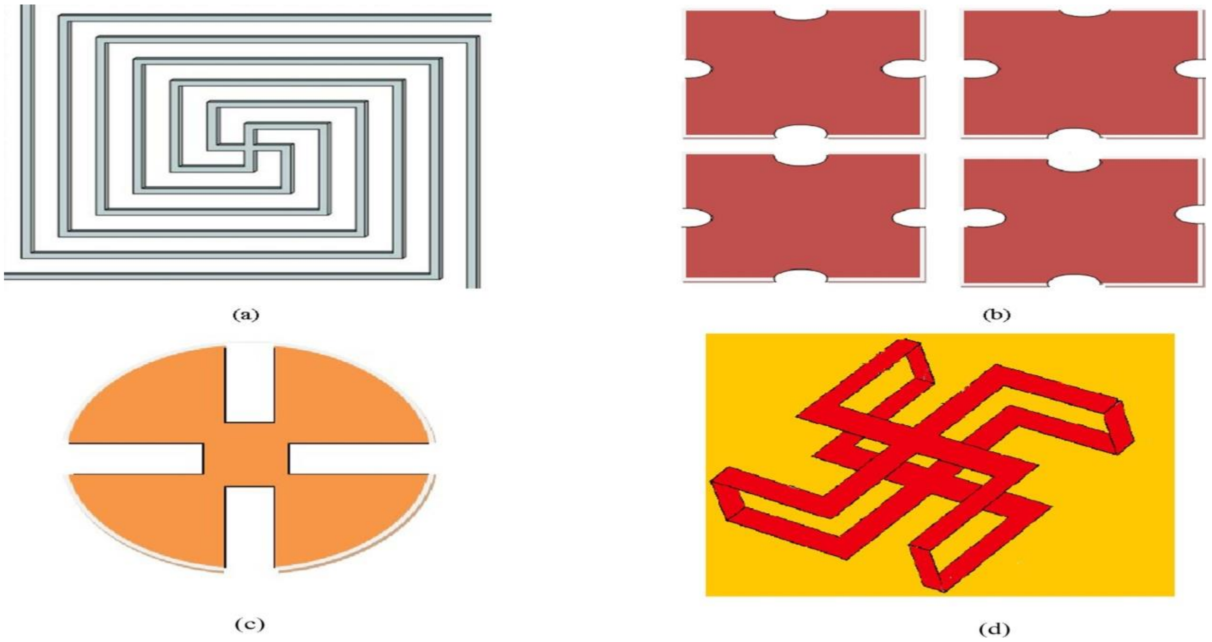


Figure 2. 6 : (a) Convoluted meandered cross dipole element[45],(b) Convoluted square loop[46], (c) Convoluted circular loop[47] and (d) 3-D miniaturized swastika element[48].

2.2.1.3 Fractal Based FSS's

Nowadays, significant research in microwave engineering is reported in the design and development of new FSS designs based on the theory of fractal geometry due to its attractive features[49,50]. Geometric patterns generate fractals through an iterative procedure for an infinite number of times[51]. However, pre-fractal shapes originate by truncating the iterative method after a finite number of iterations. FSS with fractal elements was originally proposed in[52]to cut down the size of the structure by applying the space-filling curves of Hilbert and Minkowski. Later, the innovation in recently researches has brought unprecedented prospects for engineers to investigate unlimited possible fractal configurations that had not existed in earlier time. Important performance attributes that are realized by fractal arrays include efficient methodologies to element size reduction, multi-band behavior, low-side lobe designs, and improvement in fast beam forming algorithms by utilizing the recursive property of the fractals[53,54].

Table 2. 1 : Different types of fractal and meandered FSSs.

FSS Ref.	Layers	F_r(GHz)	Array Element Size	Total Thickness	FBW %	Iteration	Patch and Aperture Element
[49]	1	15	0.377λ	0.075λ	37	1	Minkowski fractal patch
[55]	1	4	0.058λ	0.012λ	101	--	Meandered spiral lines nested with neighborhood
[565]	1	0.96	0.11λ	0.005λ	14	1	Bouble square loop (first iteration) with folded strips at the four corners
[57]	1	2.73	0.293λ	---	23.8	1	Circular and cross dipole conductive fractal patches
[58]	1	11.95 (stop Band)	0.2λ	0.002λ	4.2	1	Concentric double Minkowski fractal
[59]	1	2.02	0.012λ	0.162λ	31	SFD = 1.8617	Teragon fractals

Table 2.1 details different types of fractal and meandered FSSs when comparing structure dimensions and performance paramaters.

2.2.2FSS based on structures:

Based on the structure, we review four types of FSSs , including single layer FSSs, multilayer FSSs, antenna-filter-antenna FSSs, and three-dimensional FSSs.

2.2.2.1Single layer FSSs:

Single layer FSSs are composed of two-dimensional array of periodic resonant element. As is well known, FSSs act as either passband or stopband filters based on the two characteristics exhibited by the patch or slot elements. Single layer FSSs with such filter response have been used in wide range of applications. However, their potential use is restricted by the limited space available for the unit cell. Hence, arranging a high count of large-sized array elements and creating a better performing finite FSS is exigent. Additionally, large inter-element spacing and element sizes may result in many challenges particularly in the realizing curved surfaces[55]. For that reason, the conception of miniaturized array element FSSs is emerged and enhanced the angular stability of the structure. Such miniaturized elements are considerd broadly, because they cause the working bands to be separate from the grating lobes region as defined by the period of the array[52,60]. Recently, FSS miniaturization has been achieved by different elements, such as simple loops, multi-poles, patches, or their complementary structures, convulted, meandered, and fractal elements.

2.2.2.2Multi-layer FSSs:

Multilayer or multi-screen FSSs figure(2.7) are used to obtain certain specific behaviors. They consist of a stack of two or mor interfaces with metallic and/or dielectric patterns. In the case of a single layer FSS, it is difficult to improve the bandwidth behavior for some applications that require

a wide transmission or reflection band and a fast transition between the two bands, multilayer FSSs present a solution for these problems[61,62].

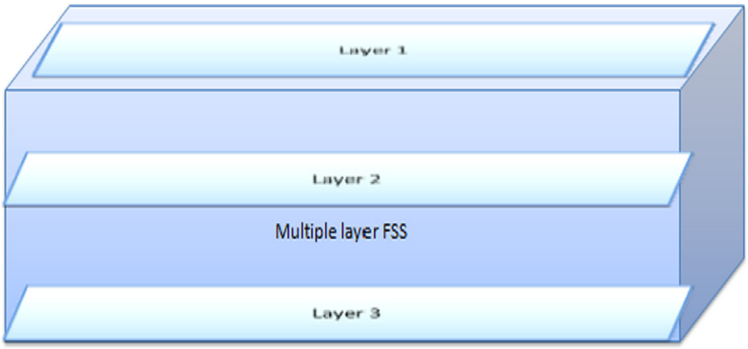


Figure 2. 7 : illustration of multi-layer FSS geometry [37, 38, 39].

Table 2. 2 : Different multilayer FSSs.

FSS Ref.	Conductive Layers	F_r(GHz)	Array Element Size	Total Thickness	FBW %	order	Patch and Aperture Elements
[63]	3	10	0.15λ	0.033λ	20	2	Inter-digital capacitance patch with wire grid
[64]	5	16.5	0.104λ	0.22λ	10	2	Capacitive patch and inductive wire grid
[47]	3	3.8	0.076λ	0.038λ	10	2	Patches of outer square ring with four inner stepped-impedance transmission lines and wire grid
[65]	2	2.4	0.104	0.013	29.2	--	Meandered lines (printed patterned wires) and 4 symmetric square metal patches
[66]	3	10.4	0.225λ	0.035λ	23	3	Capacitive patches & hybrid resonator (wire grid& balanced spiral resonators)
[67]	3	10.8	0.144λ × 0.125λ	0.075λ	75	2	Connected capacitive patches and slots of modified triples
[68]	2	1.42	0.0378λ	0.0013λ	37	--	Four-fold symmetric meander lines and convoluted dipole
[45]	4	21	0.21λ	0.273λ	5	2	All wire grid layers
[69]	3	10	0.1λ	0.067λ	21	2	Double concentric square loops patch with wire grid
[70]	3	8.5	0.2λ	0.257λ	15	3	Wire grid and hybrid (I-shaped) resonator
[71]	2	15	0.3λ	0.545λ	13	2	Gridded square loop and cross-loop aperture embedded in five dielectric substrate layers
[72]	2	7.95	0.12λ	0.042λ	23	--	Crossed slot element convoluted three circles with vertical vias

Table 2.2 demonstrates a comparison of different multilayer FSS presented in recent researches, and it is observed that achieving higher FBW is a challenge with smaller unit size and reduced profile.although multilayer construct helps to achieve the optimum design, getting higher BW at lower operating frequency is a major obstacle for the FSS designers.

2.2.2.3Antenna-Filter-Antenna(AFA) FSSs

A traditional FSS or a first-order FSS cannot cover the demands of wider BW. Additionally, by cascading multiple first order FSSs layers with the interval of quarter wavelength between each other, multi-pole or wideband FSS can be obtained as we can see in the figure (2.8). Resultantly, this technique of the adding dielectric slabs enlarges the thickness of the FSS. The use of advanced FSSs configurations, such as active FSS,fractal FSS, and multilayer FSS, may significantly enhance the bandwidth[73]. Another option of designing a multiband FSS can be accomplished by multilayerd surfaces. It has been proved earlier that fractal structures are employed for size reduction, while the stacking models can improve the bandwidth of FSS[36,49,46].

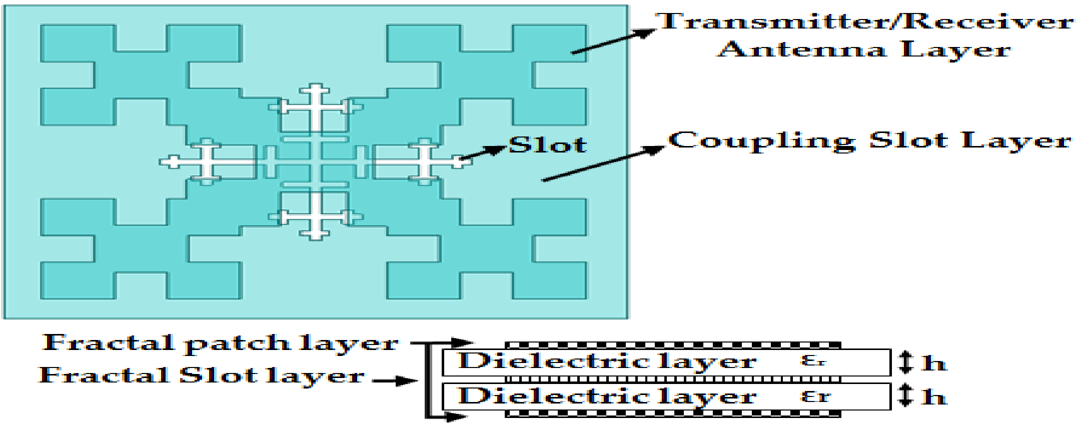


Figure 2. 8 : The configuration of fractal Antenna-Filter-Antenna(AFA) base FSS with top and side view [74].

Table 2.3 : comparison of Antenna-filter Antenna –fractal FSS structures

FSS Ref.	Conducting Layers	F_0 (GHz)	Array Element Size	Total Thickness	FBW %	Order	Patch and Aperture Elements
[75]	5	10	0.25λ	0.267λ	37	3	Minkowski fractal patch with slot ground
[74]	3	5.1	0.2λ	0.07λ	19.6	2	Minkowski fractal patch with slot ground
[76]	3	36	0.632λ	0.116λ	8.25 (1 dB)	--	Hexagonal patch and CPW quarter wave resonator (U slot)
[77]	3	10	0.25λ	0.23λ	60	3	Fractal patch with slotted ground

A comparison of recently demonstrated AFA based FSSs structues is presented in table 2.3 elaborating layers count, patch / apertures fractal shapes, and functionality. It can be inferred that AFA based FSSs are helpful in the enhancement of BW, especially when the fractal geometries are utilized in the array element. However, such structures appear to incease the thickness and/ or periodicity of the element.

2.2.2.4 Three-dimensional FSSs(3D FSSs)

Generally, the required qualities of an FSS are wide passband, fast roll-off (sharp edges), and insensitivity to incident angles and polarization of an incoming EM wave in applications, such as RCS reduction, terahertz sensing, EM compatibility, and telecommunication. Unfortunately, two-dimension periodic elements(patch/ apertures), planar FSSs(2D FSS) with the single layer or multilayer are inefficient to realize all of the above-mentioned features simultaneously[78]. Although such structures are easy to manufacture, but the inability to provide satisfactory performance, restricts these in many potential applications. Recently, a unique class of FSSs, distinguished from traditional FSS, has been introduced as 3D FSSs to beat the limitations of 2D FSS as shown in (figure 2.9)[78,79].

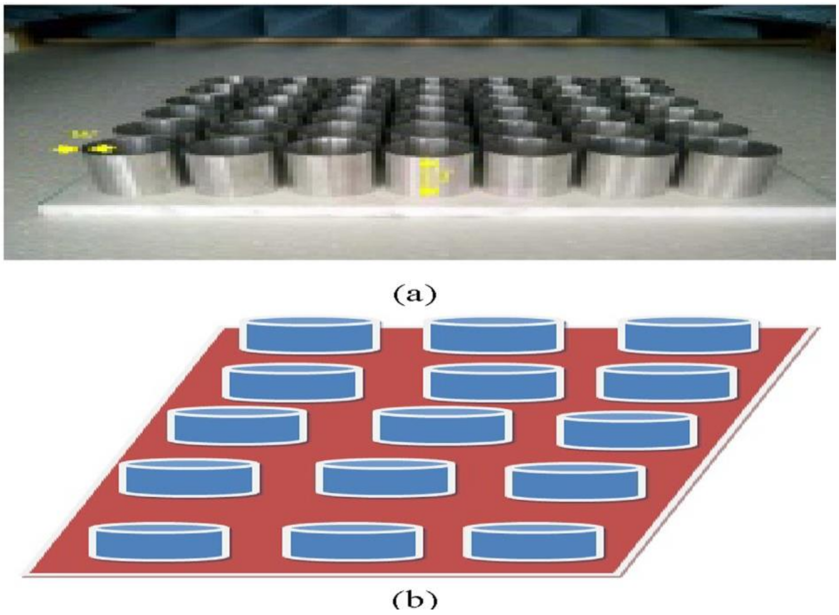


Figure 2. 9 : (a) Fabricated 3-D cylindrical FSS structures [80]. (b) Simulated 3-D cylindrical FSS structures [80].

2.3 Applications of FSS

As the name suggests, the main application of an FSS is its selective shielding, by carefully choosing the shape and size of the FSS patterns, the desired frequency can be obtained. It is for this reason that these structures have found wide application throughout the microwave field. In the following section, some applications of FSS are mentioned.

- **WIFI Wave Insulation**

FSS have been used to block or transmit the 2.4GHz WIFI band. In[81]an FSS was designed to control the WIFI band in a room by printing it on its walls. In [82] an FSS was fabricated to block the penetration of WIFI waves in a building.

- **The screen door of the microwave oven**

The microwave oven also offers an example of the use of a periodic structure. There is a kind of mesh in the glass door that serves as a band-stop filter, it completely reflects the electromagnetic energy at 2.45GHz while letting the light pass through to be able to see the food in the oven (figure2.10). In [82], an FSS was designed to transmit the 10GHz band and block the other frequencies.

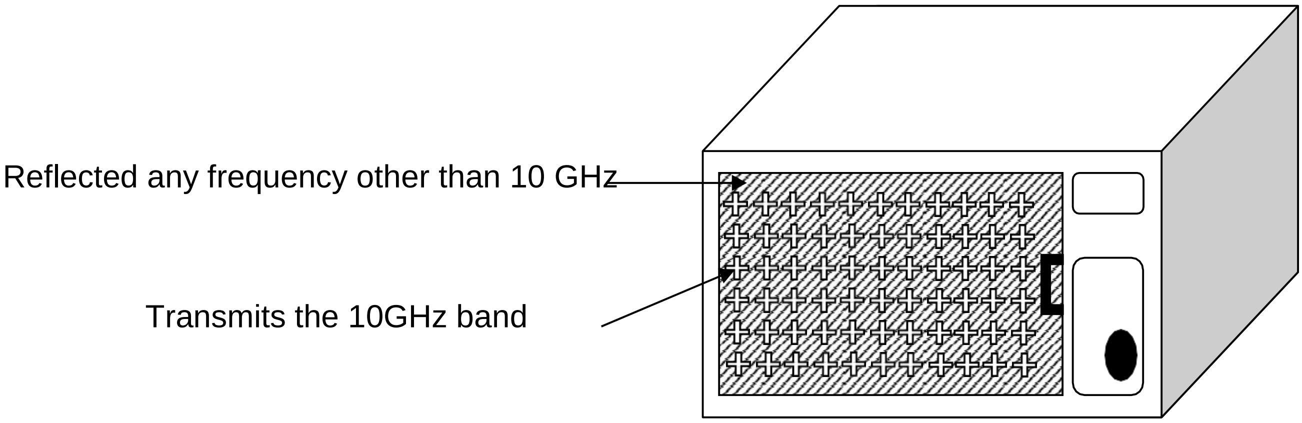


Figure 2. 10 : Screen door of a microwave oven with an FSS wall [26].

- **Radomes**

FSS are inserted in Radomes which are primarily designed to protect an antenna from the weather(figure 2.11). In this case, these structures are used to produce a bandpass filtering, which ideally lets through all the radar information necessary for the operation of the antenna, but nothing that could cause disturbances and hinder its proper operation[35]. It also reduces the radar effective area(REA) of the antenna its operating frequency band. This last application is also used in fighter aircraft to allow them to operate without the knowledge of a potential enemy's radar, which is one of the objectives of military technology research[41].

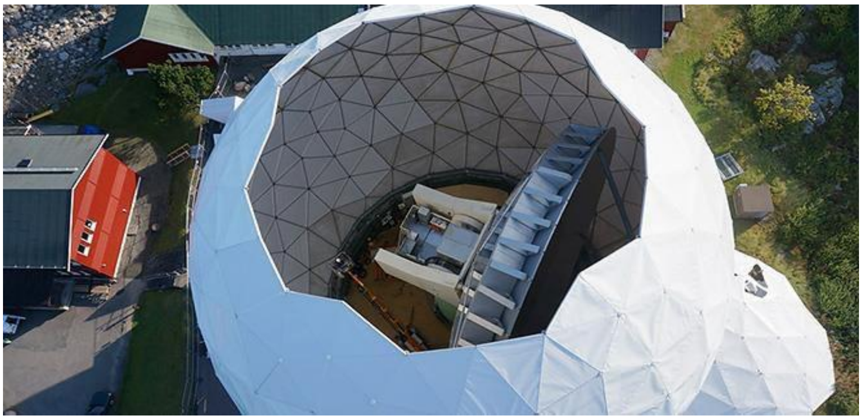


Figure 2. 11 : Rigid Radome [83].

- **Satellite Communications**

FSS have proven themselves as a method of increasing the capabilities of satellite communication that require operation in multiple bands. They are often used in space applications because of their ability to allow signals, in different frequency bands to use a single parabolic reflector[84,85].

2.4Microstrip filters

For several years, planar filter have been the subject of numerous studies. Microstrip filters can be classified into three categories:

- Localizes elements filters.
- Linear resonator filters.
- Non-linear resonator filtert(patch type).

2.4.1 Localized elements filters

An element is considerd to be localized when its physical dimensions are much smaller than the wavelength of the order of 1/20th[27,86]. Localized element filters correspond to the direct transcription of an equivalent model in low microwave frequency. For example, inductances can be realized as spiral lines while capacitors can be realized using interdigitated lines where the dielectric separates the metal surfaces(figure2.12),[29,87].These filters are characterized by their high integration(MMC technology), and the small size. However, they have the disadvantage of high losses due to low quality coefficients of the localized elements[87].

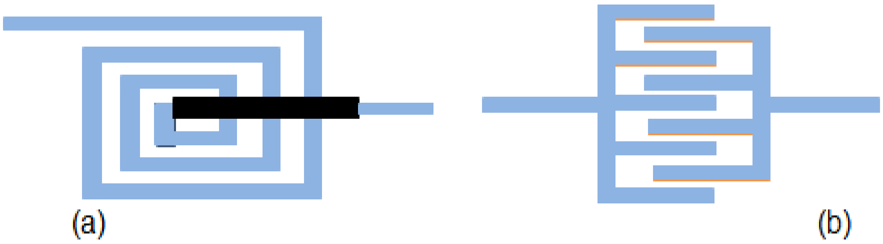


Figure 2. 12 : Localized components: (a) spiral inductance. (b)Interdigital capacitor [26].

2.4.2 Linear resonator filters

a) Coupled resonator filters

These filters are made of quarter or half-wave coupled line section$\left({}^{\lambda_g}/_2\ ou\ {}^{\lambda_g}/_4\right)$, λ_g being the guided wavelength. The length of these line segments sets the operating frequency, while the slot widths fix the level of proximity coupling[88,89].

The most well-known coupled propagation line filter topologies are:

- Capacitive coupling in series or end-to-end coupling (figure2.13a).
- Distributed or parallel coupling illustrated in (figure2.13b).

These filters can be realized in microstrip or coplanar technology. Parallel coupling can be more important than series coupling and thus allows to obtain wider bandwidths. It allows the filter length to be reduced by half compared to a series-coupled filter(at the expense width)[90].

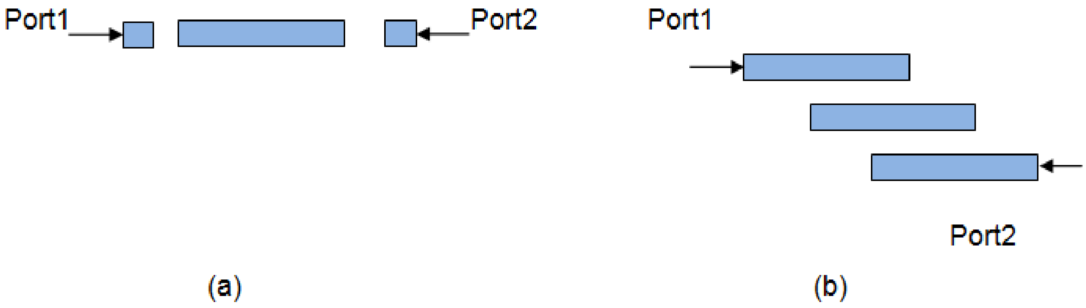


Figure 2. 13 : Coupled lines: (a) in series (b) in parallel [26].

These filters have the advantages of being fairly easy to design and adjust, however the space requirement of these structures is significant. In order to solve this problem, the U or hairpin topology is an interesting alternative(figure 2.14). These filters are based on the same operating principle as the coupled line filters[88,89].

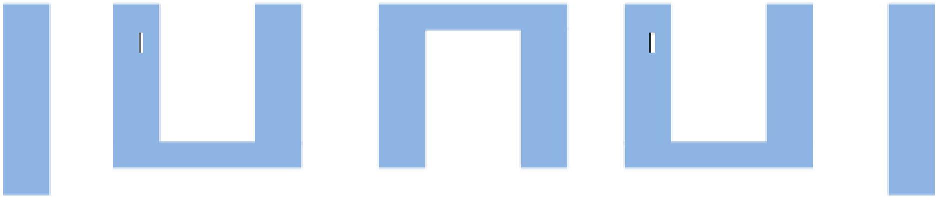


Figure 2. 14 : Hairpin filter [26].

b) Interdigital and pseudo-interdigital filters

Interdigital filters consist of parallel resonators of the same length $= \lambda_g/4$, operating in a quasi-TEM mode, each of the lines has one end connected to a ground plane and the other end unconnected as shown in (figure 2.15).

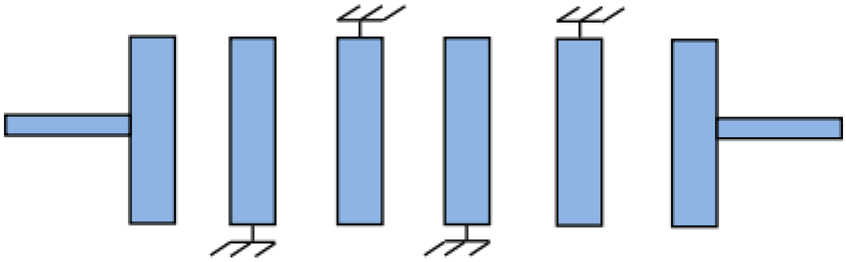


Figure 2. 15 : Interdigitalfilter[26].

Interdigital filters have the advantage of being compact and easy to fabricate, the relatively large gap between the resonators make the structure not very sensitive to manufacturing tolerance. However, they have low quality factors, resulting in high losses for narrow band filtering applications[91].

c) Stub filters

Stub filters use line sections(stub) of length $L = \lambda_g/4$ or $L = \lambda_g/2$, the width of the stub depends on the impedance to be synthesized(figure 2.16)

This topology allows to obtain high quality factors and thus low losses. It is classical, easy to master and interesting for the realization of wide band filtering functions.

Figure 2. 16 : Stub filter [26].

However, it cannot be used to synthesize filters with a small bandwidth due to technological constraints(characteristic impedance too low)[91].

2.4.3 Non-linear resonator filters(patch filters)

Non-linear resonator filters use surface resonators of various geometries, some of which are shown in (figure 2.17).Most of them work on several modes. By plaing on the geometrical shape, it is easy to design filters with original shapes and specific characteristic. These filters allow the reduction of the filter's footprint and have a good power handling[36].

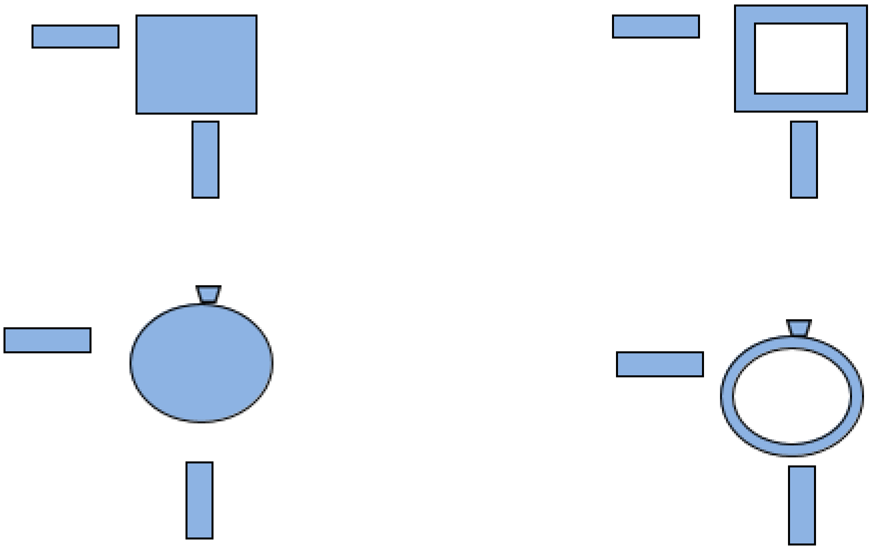


Figure 2. 17 : Non-linear resonators in different shapes [26].

2.5 Microstrip antennas

Microstrip antennas can be classified into two main categories according to the length ratio. A resonator made from a narrow conductive strip is called a dipole, while the patch is made from a wide conductive strip.

2.5.1 Radiation mechanism

To understand how a patch antenna works, consider the section given in (figure 2.18). At point "a" of the upper conductor, we consider "a" point source which radiates in all directions, part of the emmited signal is reflected by the ground plane, then by the upper conductor and so on, while some rays will be diffracted at point “b” located on the edges of the conductor.

This figure below can be devided into two distinct regions the air and the substrate:

- In the substrate between the two conducting planes, the rays are most concentrated, the electromagnetic field accumulates in this region of space.
- In the air, above the substrate, the signal scatters freely in space and contributes to the radiation of the antenna, as the surface currents flow mainly on the lower side of the upper conductor(dielectric side), the radiation is mainly emmited from the immediate vicinity of the edges. The transmission line model takes advantage of this phenomenon, since it considers the radiation from a set of fictitious slits located on the periphery of the antenna

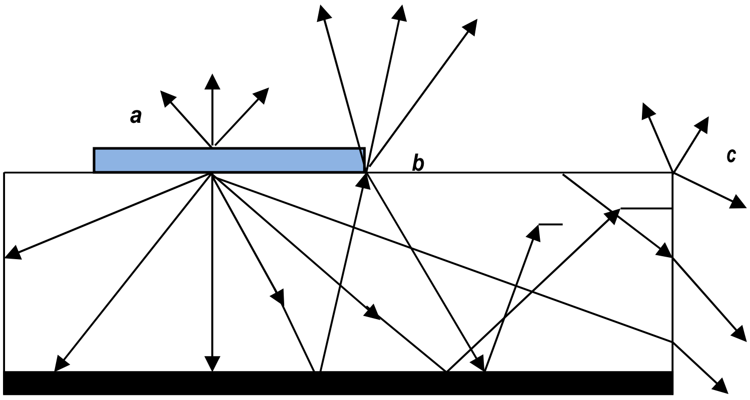


Figure 2. 18 : Radiation mechanism of a microstrip antenna [26].

Some rays reach the separating surfaces and remain trapped inside the dielectric, it is thus a total reflection. A surface wave is then guided by the edge of the dielectric, not contributing to the radiation of the antenna, however when this wave reaches the edge of the substrate(point c), it will be diffracted and will generate a stray radiation. In the case of an array antenna, the surface wave creates a coupling between the elements of the array[92,93].

2.5.2 Antenna arrays

Printed antenna arrays have attracted increasing interest in recent years, which lies in the possibility of obtaining a variable spatial distribution of radiated power compared to a single element antenna with a fixed radiation in space(unless it is mechanically rotated). This characteristic of the antenna array is possible by depositing different sources in space and by playing on the delays between the signals emmited by the different sources[94].

This type of antenna is composed of a multitude of identical and independent elements. The energy is distributed between the various sources according to a given law thanks to a splitter which distributes the signal on each element, with a known amplitude and phase. Controllable phase shifters can be inserted between the radiating elements and the splitters to form a phased array[95].

Array antennas can have several geometries: linear array, planar array and circular array(figure2.19).

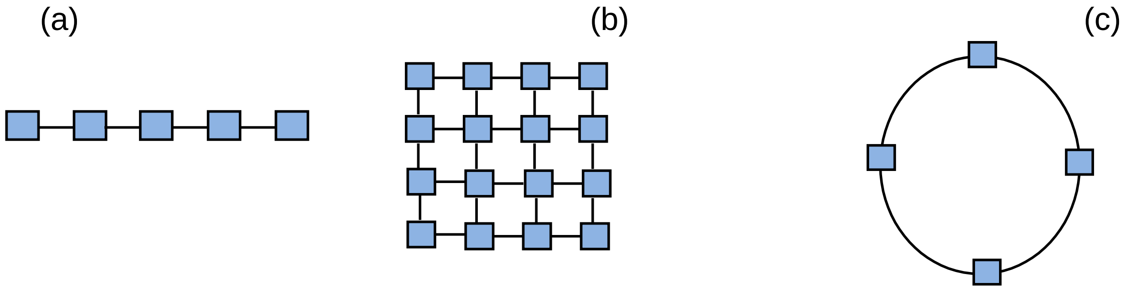


Figure 2. 19 : Different antenna array geometries: (a) Linear array (b) Planar array.(c) Circular array [26].

In the case of an array consisting of identical elements, five main parameters control the shape of the overall radiation[96]:

- The geometry of the array: linear, rectangular, circular, surface,……
- The relative spacing between each element.
- The phase applied to each excitation.
- The radiation pattern of each element.

2.6 Conclusion

The study of an important periodic structure, named as Frequency Selective Surfaces, types, and functionalities. With recent emergent trends in communication, until now, diverse research workson FSS structures have been presented. This include traditional single layer FSS, advanced multilayer FSS, antenna filter antenna FSS, three-dimensional FSS, convoluted/meandered FSS, fractal-based FSS, microwave absorbing FSS, and many other types. This range consists of simple single screen 2D FSS, with low mass, cost, and volume that can be applicable in myriads of applications, to highly complexe and advanced 3D active FSS whose superior performance can be compensated for their fabrication complexity. Extensive information in the form of tables is provided, when comparing different design techniques employed, array element structures, frequency ranges, bandwidth, and polarisability.

CHAPTER3 : MODELLING OF BASIC PHENOMENA(PHYSICS) ENTERING IN OUR FSS MODEL

3.1 Introduction to the Finite Element Method (FEM)

The description of the laws of physics for space- and time-dependent problems are usually expressed in terms of partialdifferentialequations (PDEs). For the vast majority of geometries and problems, these PDEs cannot be solved with analytical methods. Instead, an approximation of the equations can be constructed, typically based upon different types of discretizations. These discretization methods approximate the PDEs with numericalmodel equations, which can be solved using numerical methods. The solution to the numerical model equations are, in turn, an approximation of the real solution to the PDEs. The finite element method (FEM) is used to compute such approximations [97].

3.2 Comsolmultiphysics

3.2.1 History

The COMSOL Group was founded by Mr. SvanteLittmarck and Mr. Farhad [99] in Sweden in 1986. It has now grown to United Kingdom, U.S.A, and Finland and so on. Nowadays, The COMSOL Multiphysics software has been widespread used in various domains of science research and engineering calculation, for example, it was used in global numerical simulation.[98,99]COMSOL Multiphysics is a finite element analysis, solver and Simulation software package for solving various physics and engineering applications. The COMSOL Multiphysics simulation environment facilitates all steps in the modeling process: defining your geometry, specifying your physics, meshing, solving and then post-processing your results [100].

3.2.2 Introduction

COMSOL Multiphysics is an integrated environment for solving system of time-dependent or stationary second order in space partial differential equations in one, two, and three dimensions. Moreover, such equations may be coupled in an almost arbitrary way. COMSOL Multiphysics provide sophisticated (and convenient) tools for geometric modeling. Therefore, for many standard problems, there exist predefined so-called application modes which act like templates in order to hide much of the complex details of modeling by equations. The application modes make use of the language used in the respective engineering discipline [101]**.**

COMSOL (formerly known as FEMLAB) is a finite element analysis and solver software package for various physics and engineering applications, especially coupled phenomena, or Multiphysics. It includes a complete environment for modeling any physical phenomenon that can be described using ordinary or PDEs. The software package supports nearly all platforms (e.g., Windows, Mac, Linux, and UNIX). COMSOL allows for building coupled systems of PDEs. The PDEs can be entered directly or using the so-called weak form. COMSOL also offers an extensive and well-managed interface to Math Works MATLAB and its toolboxes for a large variety of programming, preprocessing, and post processing possibilities [102].

COMSOL Multiphysics is a powerful interactive environment for modeling and solving all kinds of scientific and engineering problems based on partial differential equations (PDEs). With this product you can easily extend conventional models for one type of physics into Multiphysics models that solve coupled physics phenomena and do so simultaneously. Accessing this power does not require an in-depth knowledge of mathematics or numerical analysis. Thanks to the built-in physics modes it is possible to build models by defining the relevant physical quantities such as material properties, loads, constraints, sources, and fluxes rather than by defining the underlying equations.

3.2.3 PDE Modes

COMSOL Multiphysics internally compiles a set of PDEs representing the entire model. Accessed the power of COMSOL Multiphysics as a standalone product through a flexible graphical user interface, or by script programming in the MATLAB language. As noted, the underlying mathematical structure in COMSOL Multiphysics is a system of partial differential equations. In addition to the physics mode and the modules, these provide three ways of describing PDEs through the following PDE modes:

- Coefficient form, suitable for linear or nearly linear models.
- General form, suitable for nonlinear models.

- Weak form, for models with PDEs on boundaries, edges, or points, or for models using terms with mixed space and time derivatives.

Using the application modes in COMSOL Multiphysics, that can perform various types of analysis including**:**

- Stationary and time-dependent analysis.
- Linear and nonlinear analysis.
- Eigen frequency and modal analysis.

To solve the PDEs, COMSOL Multiphysics uses the proven finite element method (FEM). The software runs the finite element analysis together with adaptive meshing and error control using a variety of numerical solvers [103].

3.2.4 Work flow

To Set Up and Run a Simulation with COMSOL Multiphysics the next work flow must done as shown in(Figure 3.1):

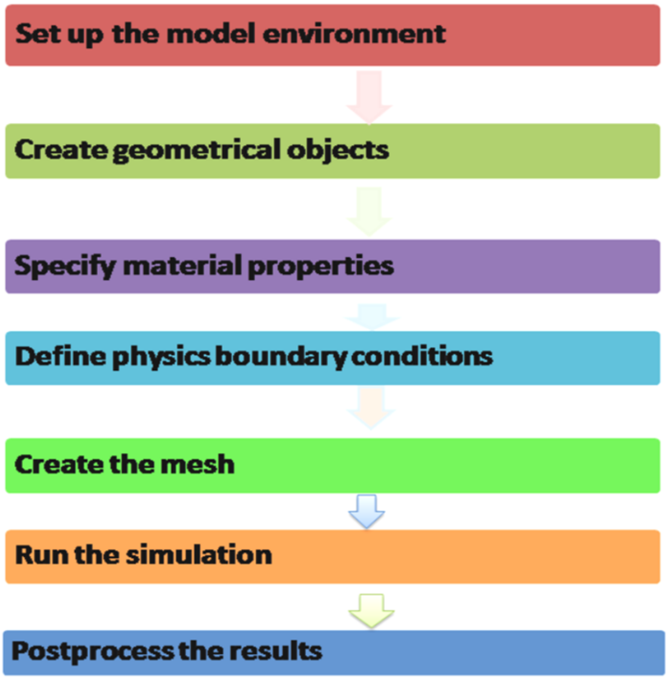


Figure 3. 1 : Flow chart of COMSOL Multiphysics [104].

3.2.5 Application areas

There are several application-specific modules in COMSOL Multiphysics. The most common applications are [98]:

AC/DC Module, Acoustics Module, CAD Import Module, Chemical Engineering Module, Earth Science Module, Heat Transfer Module, Material Library.

3.2.6 Characteristics

The spread usage of COMSOL Multiphysics in various domains largely depends on its marked characteristics. These characteristics are [98]:

- It can be used to solve multi-physics problem.
- The user can specify their own Partial Differential Equations.
- Professional predefined modeling interfaces.
- CAD models can be made directly.
- CAD package can be added.
- Exuberance of simulation capability [99].

One unique feature in COMSOL Multiphysics is something we refer to as extended Multiphysics, the use of coupling variables to connect PDE models in different geometries. This represents a step toward system-level modeling.

Another unique feature is the ability of COMSOL Multiphysics to mix domains of different space dimensions in the same problem. This flexibility not only simplifies modeling, it also can decrease execution time. In its base configuration, COMSOL Multiphysics offers modeling and analysis power for many application areas. For several of the key application areas we also provide optional modules. These application-specific modules use terminology and solution methods specific to the particular discipline, which simplifies creating and analyzing models [103].

3.3 Modelling of undercomsolmultyphysics 5.5

3.3.1 Model definition

Frequency selective surfaces(FSS) are periodic structures with a bandpass or a bandstop frequency response. This example shows that only signals around the center frequency can pass through the periodic complementary split ring resonator layer as shown in figure(3.2).

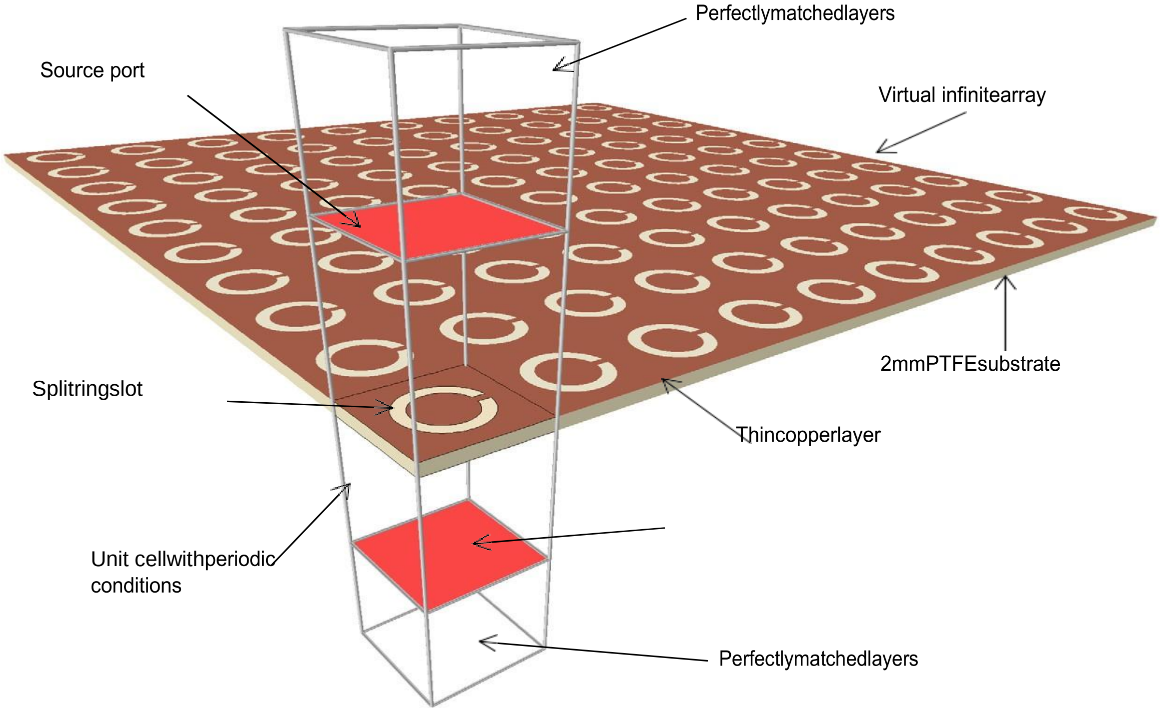


Figure 3. 2 : One unit cell of the complementary split ring resonator is modeled with periodic boundary conditions to simulate an infinite 2D array. Perfectly matched layers at the top and bottom of the unit cell absorb the excited and higher order modes.

In this pre-existed model as shown in figure (3.2), a split ring slot is patterned on a geometrically thin copper layer (which is modeled as a perfect electric conductor) that rests on a PTFE substrate that is 2 mm in thickness.The rest of the simulation domain is filled with air.

To simulate a 2D infinite array, as shown above, we can model just one unit cell of the complementary split ring resonator. This is done using Floquet-periodic boundary conditions on each of the four sides of the unit cell.

3.3.2 Model parameters

For the simulation under comsol we have chosen Parameters in the (Table3.1) below:

Table3. 1 Parameters of FSS.

Name	Value	Description
rr1	0.005 m	rr1 external radius ring
rr2	0.0035 m	rr2 internal radius ring
cell_w	0.06 m	cell_w cell width parameter >rr1
freq_center	4.6E9 Hz	freq_center
cooper_epsilon_r	2.1	_epsilon_r

After we applied the parameters of table (3.1) and with using comsol 5.5 we obtained tge geometry of figure (3.3):

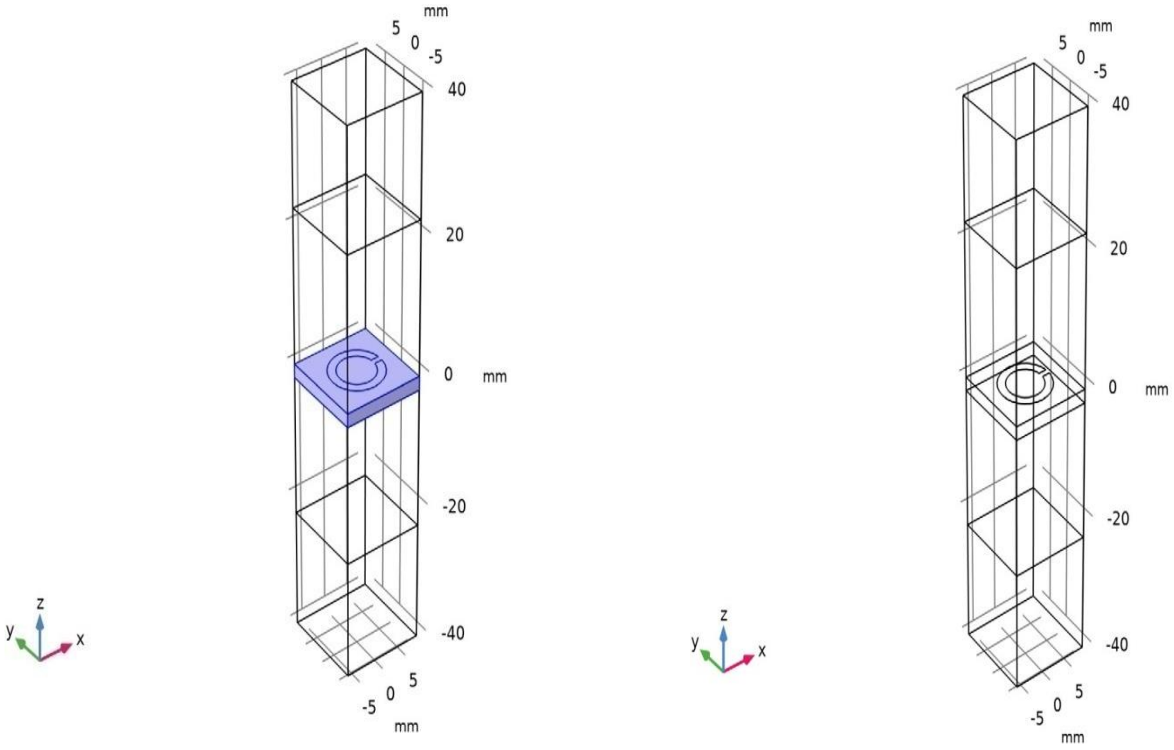
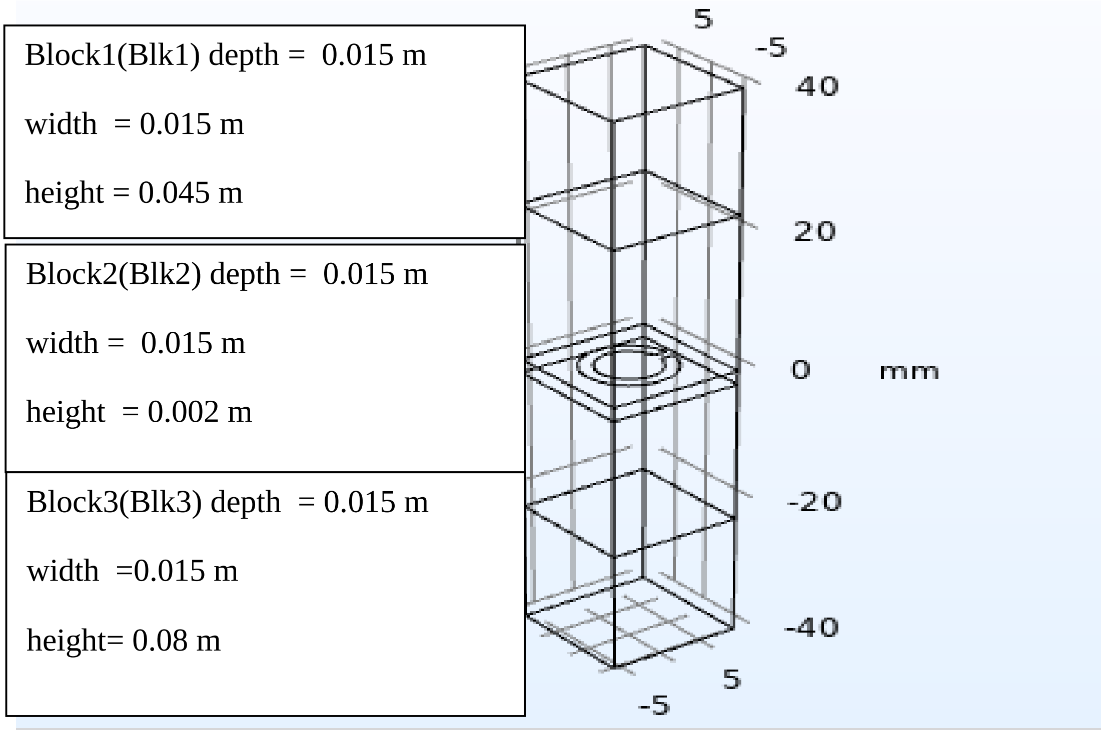


Figure 3. 3 : simulation of the FSS with comsol5.5.

3.3.3 Geometry of the model

The figure (3.4) and (3.5) shows the basic geometries of the model that we are using in this study, with different parameters.



Block1(Blk1) depth = 0.015 m

width = 0.015 m

height = 0.045 m

Block2(Blk2) depth = 0.015 m

width = 0.015 m

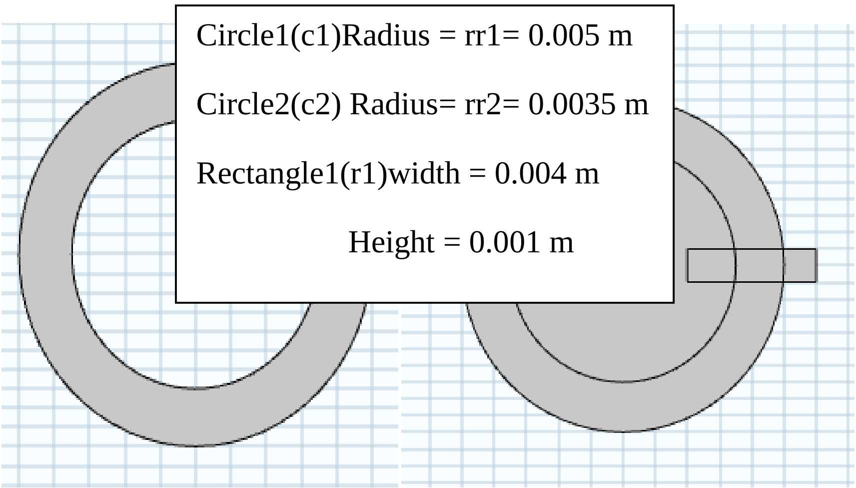
height = 0.002 m

Block3(Blk3) depth = 0.015 m

width =0.015 m

height= 0.08 m

Figure 3. 4 : Image of the geometry1 of the model using comsol5.5.



Circle1(c1)Radius = rr1= 0.005 m

Circle2(c2) Radius= rr2= 0.0035 m

Rectangle1(r1)width = 0.004 m

Height = 0.001 m

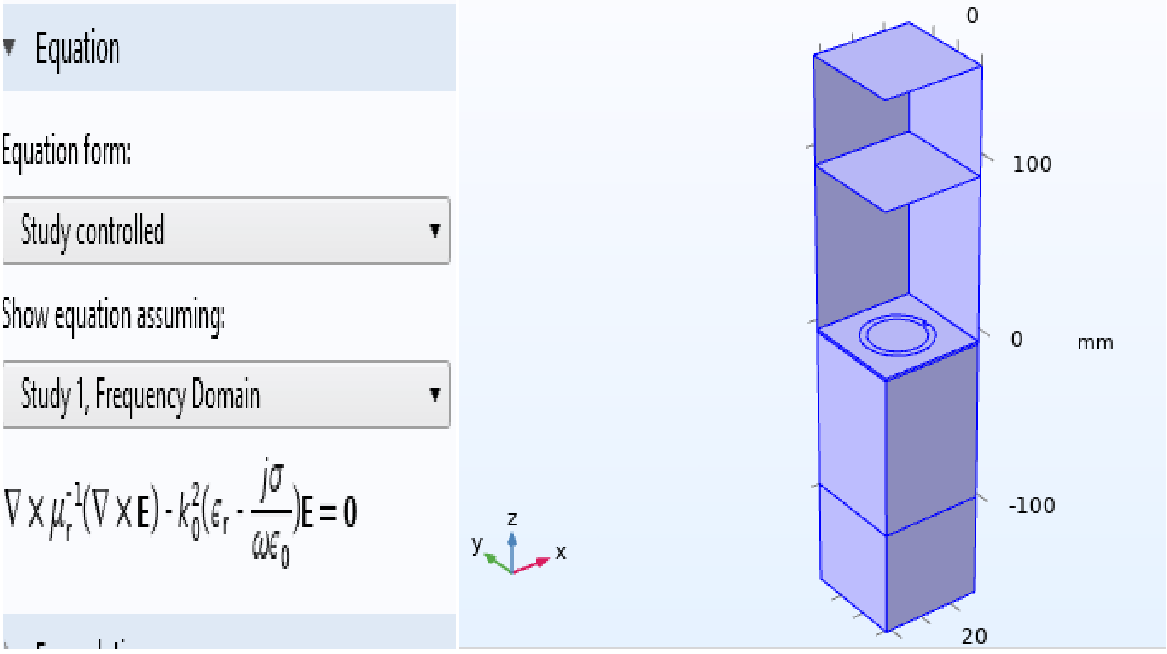
Figure 3. 5 : Image of the geometry2 of the model using comsol5.5.

3.3.4 The physics entering in our model

3.3.4.1 Electromagnetic Waves Frequency Domain(emw)

For this physics interface, the maximum mesh element size should be limited to a fraction of the wavelength. The domain size that can be simulated thus scales with the amount of avaible computer memory and the wavelength. The physics interface supports the frequency domain, eigenfrequency, mode analysis, and boundary mode analysis study type. The frequency domain study type is used for source driven simulations for a single frequency or a sequence of frequencies. The eigenfrequency study type is used to find resonance frequencies and their associated eigenmodes in resonant cavities.

This physics is used to solve the time-harmonic wave equation, (figure3.6), for electromagnetic field distributions.



▾ Equation

Equation form:

Study controlled ▾

Show equation assuming:

Study 1, Frequency Domain ▾

$$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - k_0^2\left(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0}\right)\mathbf{E} = 0$$

Figure 3. 6 : Electromagnetic Wave Frequency Domain

The electromagnetic wave is propagating in the x-y plane, with the electric field polarized in the z-direction. Assuming that the modeling domain is purely vaccum, the frequency domain Maxwell's equations reduce to:

$$\nabla.(\mu_r^{-1}\nabla \mathrm{E_z}) - \mathrm{k}_0^2 \varepsilon_\mathrm{r} \mathrm{E_z} = 0 \qquad (3.1)$$

WhereE_z is the electric field, relative permeability and permittivity$\mu_r = \varepsilon_r = 1$ in vaccul, and$k_0 = \omega\sqrt{\varepsilon_r\mu_r} = \frac{\omega}{c_0}$ is the wavenumber.

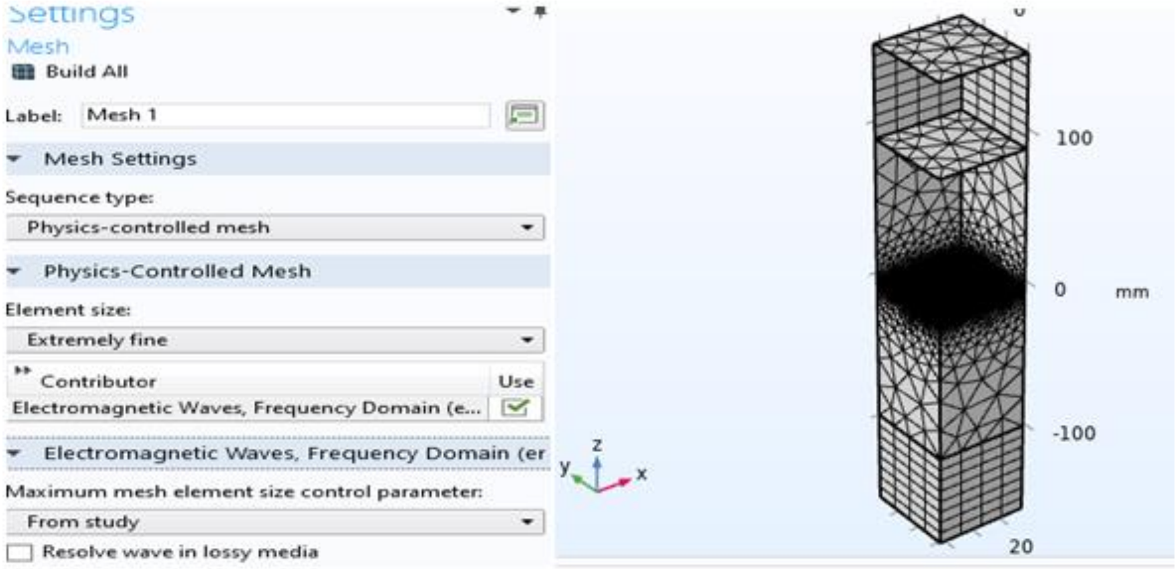
- **The Scattering Boundary condition**

One of the first transparent boundary conditions formulated for wave-type problems was the Sommerfeld radiation condition, which can be written as:

$$\lim_{r\to\infty}\sqrt{r}\left(\frac{\partial E_z}{\partial r}+ik_0E_z\right)=0 \tag{3.2}$$

3.4.5 The Meshing

The maximum mesh element size in dielectric media is that in free space divided by the square root of the product of the relative permittivity and permeability, (figure3.7) .



Label: Mesh 1

Sequence type: Physics-controlled mesh

Element size: Extremely fine

Contributor	Use
Electromagnetic Waves, Frequency Domain (e...	☑

Maximum mesh element size control parameter: From study

☐ Resolve wave in lossy media

Figure 3. 7 : The meshing of the model.

3.5 Conclusion

In this chapter we had tried to modelateand change the parameters of our pre-existed FSS model (geometry2) which contains several studies which makes the task a little bit difficult because when we treat several studies the simulation under comsol5.5 becomes too much difficult and take a very long time, so after several attempts we managed to make this simulation to be able to exploit the results.

CHAPTER4 : RESULTS AND DISCUSSION

4.1Parameters

(Note): We present the results of the simulations by changing the parameters of the pre- existed model table(4.1) to decrease the resonance frequency .

Table 4. 1 the initial paramaters of the pre-existed model.

Name	Value	Description
theta	0 rad	Elevation angle
Name	Value	Description
rr1	0.005 m	rr1 external radius ring
rr2	0.0035 m	rr2 internal radius ring
cell_w	0.06 m	cell_w cell width parameter >rr1
freq_center	4.6E9 Hz	freq_center
Cooper_epsilon_r	2.1	Cooper_epsilon_r

4.2 Electric field(emw)

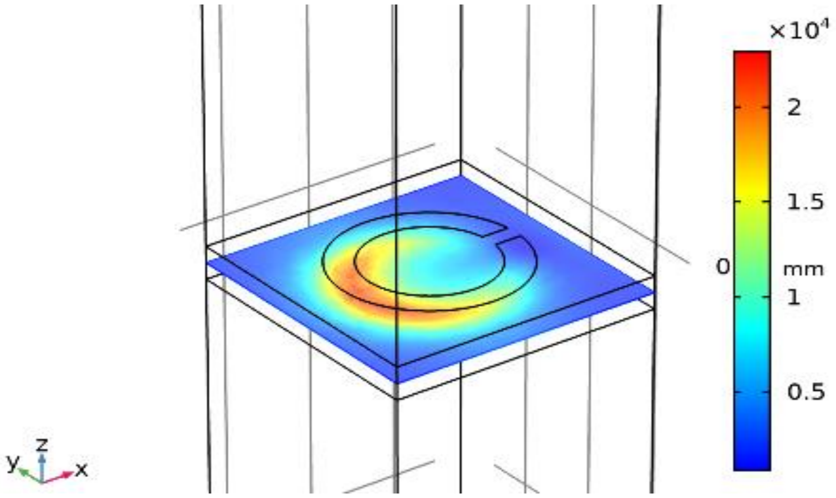


Figure 4. 1 : Multislice electric field norm (V/m).

(Figure 4.1) shows that the electric fields norm are confined in the split ring slot.

4.2 S-parameter (emw)

S parameter is a parameter related to high frequency microwave circuits and denotes the properties of the network under high frequencies. It can be denoted as the transmission co-efficient, reflection co-efficient and help in ports.

S11 (Return Loss): Return loss is defined as the destruction of signal power result from the rumination caused at a discontinuity of transmission line or optical fiber. This discontinuity can be a mismatched with the help of load or a device.

$$\mathrm{RL(dB)} = 10\log10\, \mathrm{p_i}/\mathrm{p_r} \qquad (4.1)$$

S21 (Forward Transmission Co Efficient): It is the attenuation based on the wave travelling from port 1 to port 2.It has S21 has given by:

S21=(b2/a1) where a2=0

The figure (4.2) shows that the frequency decrease every time we increase the dimensions of the geometry.

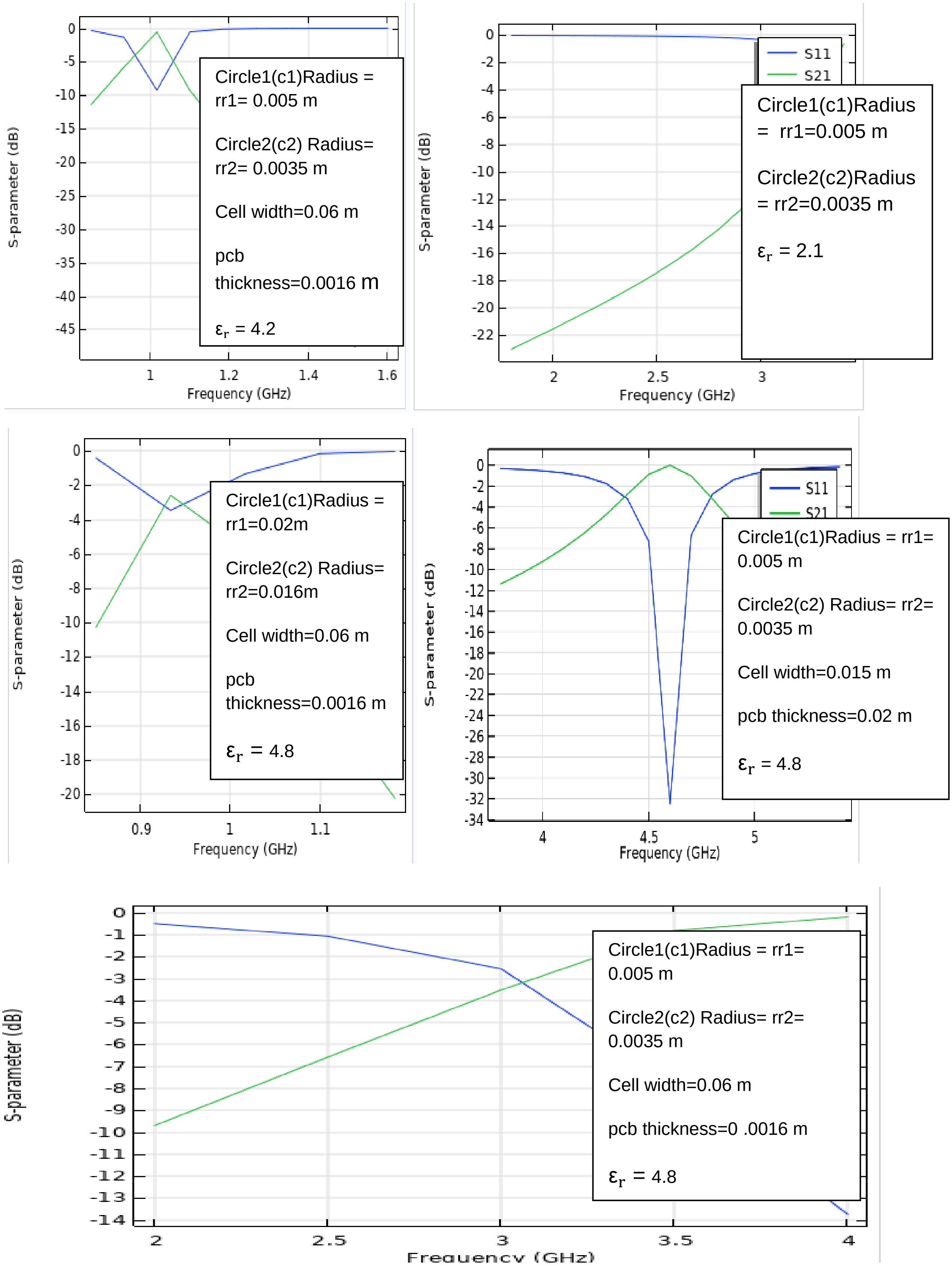


Figure 4. 2 : The s-parameters plots.

4.2.1Discussion

The S parameter plot in figure(4.2) shows that this periodic structure functions as a bandpass filter near to the resonance frequency.

4.3 Smith Plot(emw)

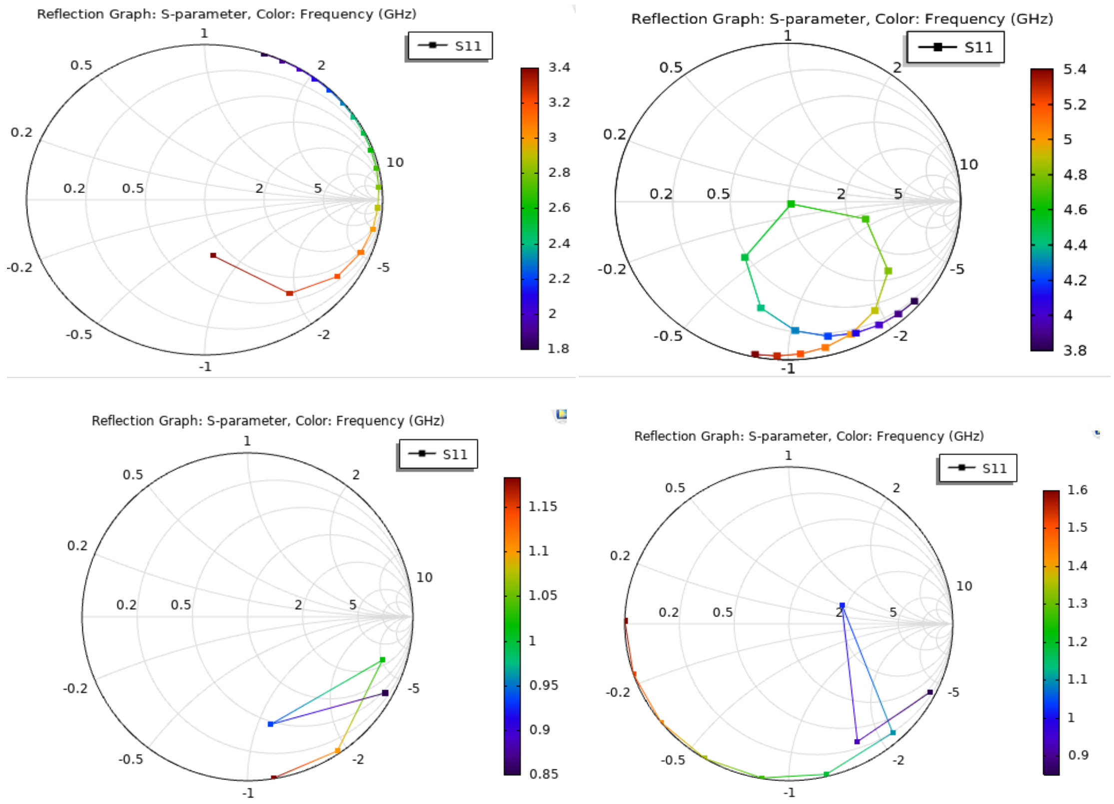


Figure 4. 3 : Reflection graph: S-parameter, color : frequency (GHz)

In figure (4.3) the Smith plot has been created to evaluate the reflectivity and transmittivity performance of the FSS model with different incident angles

GENERAL CONCLUSION

In this work we try to simulate a user-specified periodic structure chosen from the built-in unit cell types with electromagnetic waves.

We modeled the pre-existed model to obtain a resonance frequency adapt to L band 1GHz and less and after so many attempts we obtained the desired results by changing the parameters of the model.

We had tried to modelate and change the parameters of our pre-existed FSS model wich contains several studies wich makes the task a little bit difficult because when we treat several studies the simulation under comsol 5.5 becomes too much difficult and take a very long time , so after several attempts we managed to make this simulation to be able to exploit the results.

By changing the width of the elementary cell we were able to decrease the resonance frequency from 4.6 GHz to 0.93 GHz , and that because the relation between the frequency(f) and capacitance(c), so when we decrease the width of the elementary cell(e), the capacitance increase and as a result the frequency decrease.

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