DESIGN AND ANALYSIS OF SUN-SHAPED LPF USING CSRR

A PROJECT REPORT

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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Submitted by:

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CANDIDATE'S DECLARATION

I, Maytok Lazes, Roll No. 2K16/MOC/07 student of M.Tech. (MICROWAVE AND OPTICAL COMMUNICATION), hereby declare that the project Dissertation titled **"DESIGN AND ANALYSIS OF SUN-SHAPED LPF USING CSRR"** which is submitted by me to the Department of ELECTRONICS AND COMMUNICATION ENGINEERING, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associate ship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled **"DESIGN AND ANALYSIS OF SUN-SHAPED LPF USING CSRR"** which is submitted by MAYTOK LAZES, Roll No 2K16/MOC/07 Department of Electronics And Communication Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi **Dr.PRIYANKA JAIN**

Date: **SUPERVISOR**

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ABSTRACT

Metamaterials are artificial metallic structures having simultaneously negative permittivity (ε) and permeability (μ), which leads to negative refractive index. Due to negative index it supports backward waves i.e. inside Metamaterial phase velocities and group velocities are antiparallel. Metamaterial doesn't obey Snell's law, Doppler effect, Vavilov-Cerenkov radiation etc. No other material in the world shows the above properties like Metamaterial. Due to these unusual properties Metamaterial can change the electric and magnetic property of electromagnetic wave passing through it and because of these reasons when Metamaterial is used in the fabrication of microwave components and antennas the required properties can be enhanced. Also miniaturization in the size of the component is possible as the structural cell size of Metamaterial is less than one-fourth of the guided wavelength.

With the basic knowledge of metamaterials where used to design a LPF using sun-shaped CSRR. In microwave systems, LPF is regularly used to get rid of the undesired frequency. Step impedance low-pass filter and open stub low pass filter are generally utilized for this reason. Yet these low pass filter have steady cut-off response. By expanding the number of areas, the rejection characteristics can be better. However, by expanding the number of sections, the pass-band insertion loss increases and also the physical size of the overall filter increase. A few strategies have been accounted to tackle this issue. So a new artificial material is used which is known as metamaterials, using the properties of these unique properties a compact size filter can be designed. The designed LPF using sun-shaped resonator with eight slot of equal size at equal distance from each other has been designed. This designed filter has low insertion loss and sharp cut of frequency at 1.69 GHz. The low pass filter was designed on a FR-4 (lossy) substrate with a height of 1.6mm and the relative permittivity of 4.30. The filter designed has eight slots of equal size giving a sun shape which are etched on the ground plane of the substrate. The designed filter has low pass band insertion loss and a sharp cut off frequency at 1.69 GHz. Thus a sun shaped low pass filter with compact size is designed and simulated in CST Microwave Studio. The low pass filter is fabricated and tested to verify the results attain from the simulation.

This designed filter can be utilized in microwave to reject the undesired frequency in microwave systems. Moreover the designed low pass filter is compact and small in size

as compared to the conventional low pass filters designed which makes a component more efficient and helps in future technology for making miniaturized components for wireless communication. Due to size miniaturization of the components, more and more number of filters can be fabricated in a small region to lessen the cost and material utilized for the last fabricated microwave components

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
MTMs	Metamaterials
LPF	Low Pass Filter
SRR	Split Ring Resonator
CSRR	Complementary Split Ring Resonator
TL	Transmission Line
CRLH	Composite Right and Left Handed
EW	Electromagnetic Wave
NRW	Nicolson Ross Weir
PEC	Perfect Electrical Conductor
PCB	Printed Circuit Board
VNA	Vector Network Analyzer

CHAPTER -1

INTRODUCTION

1.1 OVERVIEW AND MOTIVATION

With fast development and vibrant study of metamaterials, they generated more interest for the investigation of metamaterials and its related applications in the technological world. Metamaterials are artificially designed materials which acquire exceptional properties readily unattainable in natural materials. The material shows a property distinguished by the negative permittivity and permeability at the same time in a particular range of microwave as well as optical frequencies. This type of medium exhibited negative permittivity and permeability due to that negative refractive index was first discovered and initiated in 1968. This left-handed material exhibited a number of unique and unusual properties which purely supported backward wave propagation. MTMs obtained their properties from the designed structures rather than their compositions.

With these unusual material properties, metamaterials have become very useful in the field of upcoming technologies. With these exceptional properties, new kinds of miniaturized antennas and microwave devices can be designed which is very useful for the wireless communication and defence industries. The property exhibited by the left-handed materials have also been used in the designing of light, invisible cloaks, and sound filtering devices, superlenses, wave absorbers and various other microwave passive devices which are being developed using the present technology. Metamaterils are also being used to enhance the performance of microwave components in the wireless communication systems.

Nowadays, filter plays a crucial role in the wireless communication systems such as radar, radio devices for communication, navigation systems, and sensing, medical instruments and in many radio frequency circuits. These filters are used to pass the particular band of frequency and reject the unwanted band of frequency which is based on the filter response and the communication requires. Practically filters are designed to select and reject or to combine and separate the signals at various band of frequencies. Filters which are designed by the normal method, using lumped elements like capacitors and inductors are very bulky, expensive and it is very difficult to use practically and thus making them hard to implement in the wireless communication devices. To solve these issues there have an emergent utilization of this unique man-made material known as metamaterials (MTMs) structure such as complementary split ring resonator (CSRR), omega shape resonator and etc. In the present time wireless communication has been growing number of users have led to huge demand bandwidth and data rates. Because of high demands of this bandwidth maximum communication systems are in range of microwave frequencies, these filters are most important elements to have excellence frequency selective devices. Thus it has led to the growth of the wide band pass, stop band and low pass filters in emerging technologies for the various radio and wireless communication systems. The filter applications are tremendously being used in various microwave components, the filters with more requirements such as it should have low insertion loss, high selectivity, linear phase, low cost of manufacture and small size have increased. Thus compact size microstrip filters are required so that the designed communication devices are small in size having a high packing efficiency and thus reducing the cost and material required for manufacturing the components. The introduction of the concepts of metamaterial has also allowed a conventional approach of designing a microstrip filter to a newer design filters approach with improved performance characteristics and smaller size.

1.2 RESEARCH OBJECTIVES

Recent advancement in mobile and satellite communication requires the miniaturisation of system dimensions without affecting electrical performance. The work presented in this thesis firstly focuses on reducing the size and fabrication complexity in designing a LPF while maintaining same frequency response. The first objective of this thesis is to study the basics of metamaterials, understand the unique property exhibited by them and how these materials are practically realized with their applications. The second objective is to design a LPF using sun-shaped CSRR with low pass band insertion loss.

1.3 LITERATURE REVIEW

MTM was produced in 1967 by Russian scholar Victor Veselag. He expressed, in spite of the fact that LH materials don't present in nature, Veselago reasoned the acknowledgment of LH Metamaterial shall conceivable by improving an isotropic negative µ material in his paper. Enthusiasm for Veselago‟s paper and LH materials starts appear when Professor Pendry at Imperial College exhibited primary non-ferrite negative µ Metamaterial in light of SRRs in 1998 Pendry’s SRR was foundation of a main mass LH Metamaterial acknowledgment by gathering at University of California, San Diego in 2000. Thus Metamaterials are artificial material have all the while negative permittivity and penetrability. In 2003, the transmission approach by outlining unit cell was proposed by Caloz, Oliner and Eleftheriades. The exploration began an outline resounding reception apparatuses utilizing Metamaterials. For MTMs the basic normal cell estimate is short of what one-fourth of the guided wavelength in view of this property high level of scaling down is conceivable in receiving wire outline. When all is said is done MTMs can be acknowledged utilizing SRRs with thin wires however these are unreasonable for reception apparatus purpose transmission line unit cells are utilized as part of receiving wire planning.

1.4THESIS OUTLINE

The main outline of this thesis is given as follows:

Chapter 1: This chapter is titled as “Introduction” and consists of overview, motivation, the literature review, methodology and the research objectives.

Chapter 2: This section includes the introduction to Metamaterials, and essential ideas of Metamaterials, for example, exceptional properties like at the same time negative permittivity and permeability.

Chapter 3: This section includes the outline of Metamaterials based Transmission lines.

Chapter 4: This chapter contains the filter theory.

Chapter 5: This section includes the design and simulation of low pass filter (LPF) using sun-shaped CSRR and this designed filter is used in wireless communication systems. This filter is designed and simulated using CST Microwave Studio Design Software.

Chapter 6: This section includes future work and conclusion of the work that a perfect microwave filter with low pass band insertion loss can be designed because of extraordinary properties of Metamaterials.

CHAPTER 2

METAMATERIAL

2.1 INTRODUCTION

The studies of Metamaterials in the field of science and engineering have gained great interest from the last 15 years and it is still the hot research topic. The new conception of meta-materials offers great opportunities to change the physical concepts of meta-materials in laboratories to innovative filter designs in practical engineering applications. With the advances creating in view of metamaterial ideas, the key performances of filters are essentially enhanced at microwave and millimetre-wave bands. Meta-materials (MTMs) are also known as Left-handed materials. Meta-materials are a man-made/engineered material which is not found in nature. Meta-materials are the only material on the planet which exhibits "negative permittivity, negative permeability and negative refractive index at the same time" [1]. Meta means beyond in Greek as they exhibits a property which are beyond nature. Metamaterials was first developed by Victor Veselago who is a Russian physicist. He also discovered a various interesting and unique optical properties for negative index mediums [1]. This metamaterials are used in many noble applications like compact and efficient antennas, waveguides and in microwave components like filters, negative index lences, invisibility cloaks, invisible submarines and many other microwave and optical devices. These are man-made metallic structures so as to have dimension considerably smaller than the wavelength of incident radiation. Metamaterials gain their characteristics from physical arrangement and geometric as opposed to its synthesis. It is pondered as one of tenth fascinating inventive objects in world owing to its unique and exceptional properties. It is specially engineered to modify the bulk of negative permittivity and negative permeability of the medium. Metamaterials got an extensive variety of potential exercises in regions, for example, communication, RD design, transmission lines, and optics. The easiest MTM structures are CRLH T-structures, SRR and CSRR. Through the mix of different types of these structures, diverse exhibitions can be achieved.

Typically metamaterials are periodic structures consisting of sub-wavelength dimensions. Hence provides a high degree of miniaturization [2, 3]. For Metamaterials, $p < \lambda g/4$, where, p is the average cell size, λg is guided wavelength.

The paths of electromagnetic waves are controlled by materials. For instance, the lens of eyeglasses is simply a bit of plastic or glass whose surfaces are in a formed positively to get a required optical ability. Materials are uniquely given optical devices shape above the electromagnetic range, from radio waves to visible light. Nature has given us superabundant material properties, out of which some are very useful to engineer an optical devices. The conventional approach is a chemical synthesis to material development, which has not facilitated the right to use entire range of material properties that should be theoretically possible.

So there is another approach, we can artificially structure a desired material by bring together the objects collectively. These artificially designed structures give out to substitute the molecules and atoms of a conventional material. Being a composite structure that can have their electromagnetic properties by combined material unnaturally. Such composite structures are called as Metamaterials.

Electromagnetic Metamaterials are artificial periodic structure and are engineered to interact and control electromagnetic waves. Electromagnetic spectrum is shown below in the figure 2.1. The most familiar EM waves are the light waves in the visible spectrum, which engage a little part of electromagnetic waves.

The wavelengths of visible light waves are from 400 to 700 nanometres, even though electromagnetic waves can have a wavelength of thousands of kilometres to trillionths of a meter.

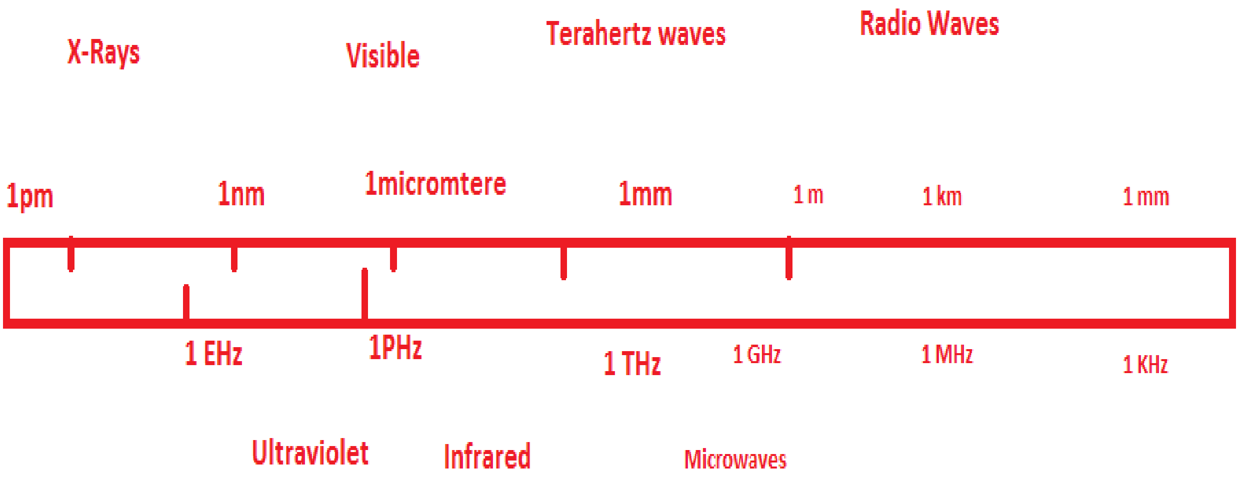


Fig. 2.1 EM Spectrum

At the point as the electromagnetic waves go into a material, the magnetic and electric fields of waves make the electrons inside the material to move around. The electromagnetic energy is exchanged with molecules and atoms of a material are the methods by which material can be utilized to impact and control light waves, framing a reason for electromagnetic devices.

The separation and size between the atoms inside the materials are the order of angstroms, or a tenth of nanometre, which implies the dimension of light waves, which are hundreds of nanometre in size and longer wavelength waves not verge to resolving the atomic structures. Despite the fact that we realize that the materials are comprised of accumulations of particles we are not capable to see the individual atoms because the light we see is much larger than the atomic scale. So we are not able to approximate the discrete atoms and molecules of a material as a continuous substance, whose properties are not only derived from the individual atoms and molecules, but from their interactions.

We can come up effectively with examples of optical devices, depend on our experiences with the visible light. The lens of eyeglasses, telescopes or in magnifying instruments are essentially bits of glasses or plastics that take the beams of light and make them to converge or diverge. The property of a lens depending on materials, lens are made and furthermore on its shape. Waveguides and optical fibres are another class of optical gadgets which are utilized to manage the light to go starting with one point then onto the next point, similar to water going through a pipe. Optical fibres are made up to a great degree unadulterated glasses by 'pulling' mindfully planned, optimized and utilized to send out light over a long distance.

The variety and class of optical devices are in part dictated by the accessible scope of electromagnetic properties of material utilized to create devices. There are intriguing open doors on the grounds that the current materials demonstrate just a little piece of electromagnetic properties that are hypothetically accessible. As we realize that in the end, materials are comprised of atoms and molecules, so it would appear to be achievable to attempt to widen the accessible scope of material properties in exchanging a composition of material at sub-atomic level via utilizing chemistry. However there is a different method to expand our meaning of a material. Actually, we can "trick" the light by making an arrangement of objects and combining them to make one structure. The spacing between objects are smaller than a wavelength of light, and the light won't have the capacity to determine the dissimilarity between a gathering of objects and an actual material. As it turns out, material properties achieved by designing the geometry of microscopic objects can increase well beyond what is accessible by chemical synthesis. As a result, a structure material is now or generally termed as MTMs, since its electromagnetic properties are unique than the available materials. The concepts of MTMs allow us to dodge the chemical synthesis methods, and an approach at novel electromagnetic materials by varying the geometry of other objects. In this thesis profundity examination was presented on a metamaterial transmission line that was acknowledged through microstrip filter with CSRR because designing a metamaterial filter is simple with considerable size reduction and improved results. This microwave filter is designed on a FR-4 (lossy) substrate as a material having thickness of 1.6mm and relative permittivity 'ε_r' equal to 4.3. The ground plane and transmission is made up of copper. The designed filter has low insertion loss.

2.2 MAJOR APPLICATION AREAS OF METAMATERIALS

- MTMs as Filter: Microwave filter is a crucial component to get free from the unnecessary signals from the system and permit the signal in precise frequency to pass through. Planar filters are commonly used because of the low profile, easy in manufacturing and also easy to apply with microwave integrated circuit.

- MTMs as antenna: MTMs coatings are utilized to improve the radiation and matching properties of miniaturized electric and magnetic dipole antennas. MTM enhances the radiated power.
- MTMs as Phase compensator: MTMs act as a phase compensator, when wave enters a double positive slab having positive phase shift while DNG slab has opposite phase shift so when wave exit from a DNG slab the aggregate phase distinction is equivalent to zero. Some other important applications of MTMs are in Microwave components, Negative Refractive index, Microwave Invisibility, Cloaks Invisible Submarines, Revolutionary Electronics and Lenses Waveguides.

2.3 THEORETICAL SPECULATION BY VIKTOR VESELAGO

The history of MTMs was begun in 1967 with a noble supposition in presence of "substances having values of negative permittivity ε and permeability μ simultaneously" [1]. "Veselago termed these "substances" left-handed (LH) to demonstrate the piece of evidence that they would permit the propagation of EM waves with the electric field, the magnetic field, and the phase constant vectors structuring a left-handed triad, compared with conventional materials in which this triad is known to be right-handed. Several fundamental phenomena [4] going on in or in association with LH media were predicted with the aid of Veselago :

1. Reversal of the boundary conditions describing the common mechanism of magnetic and electric fields at the boundary were connecting a traditional/ RH medium and LH medium.
2. Reversal of Snell's law.
3. Succeeding negative refraction at the boundary among a RH medium and LH medium.
4. Alteration of a point source into a point image by a LH slab.
5. Interchange of convergence and divergence effects in convex and concave lenses, respectively, when the lens is made LH.
6. Plasmonic articulations of the constitutive parameters of the constitutive parameters in resonant-type LH.
7. Essential frequency dispersion of the constitutive parameters.

8. Reversal of Vavilov-Cerenkov radiation.

9 Reversal of Doppler Effect

2.4 THE LEFT HANDED METAMATERIALS

Electromagnetic metamaterials are efficiently analogous man-made structure specially designed to give electromagnetic properties which is not found in natural world [5]. Effectively homogeneous means that the diffraction or scattering has a very small cause in wave propagation in MTM. Lattice constant of MTMs are substantially littler than the electromagnetic wave.

To clearly understand the concept of left-handed or metamaterial medium, we should have a proper knowledge of conventional right-hand rule in the electromagnetism. The right-hand rule of electromagnetic waves states that when the direction of the electric field 'E' is given by thumb, and magnetic field 'H' by index finger of the right hand placed at 90° to each other, then the middle finger perpendicular to both fingers give the direction of the propagation of the waves, thus normal to both electric and magnetic field. All the electromagnetic waves follow this rule and are given by the equation below:

$$\vec{E} \times \vec{H} = \vec{S} \tag{2.1}$$

$\vec{E}$ Is the electric field intensity, $\vec{H}$ is the magnetic field intensity, $\vec{P}$ is the Poynting vector and the direction of propagation of energy and wave.

To describe electromagnetic wave, let us recall the Maxwell's equations which are given below:

$$\nabla \times \overrightarrow{E} = -\frac{\partial \vec{B}}{\partial t} \tag{2.2}$$

$$\nabla \times \overrightarrow{H} = J_{c} + \frac{\partial \vec{D}}{\partial t} \tag{2.3}$$

$$\nabla \times \overrightarrow{D} = \rho \tag{2.4}$$

$$\nabla \times \vec{B} = 0 \tag{2.5}$$

Here $\vec{B}$ represents magnetic flux density, $\vec{D}$ represents electric flux density and J_c is the electric current density.

The Eq. 2.2 and Eq.2.3 can be written as:

$$\nabla \times \vec{E} = -\mu_O \mu_r \frac{\partial H}{\partial t} \tag{2.6}$$

$$\nabla \times \vec{B} = -\varepsilon_O \varepsilon_r \frac{\partial B}{\partial t} \tag{2.7}$$

Where μ_r and ε_r are the relative permeability and relative permittivity respectively, and $\nabla = \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}$. We obtain the wave equation from equations 2.6 and 2.7:

$$\nabla^2 \times E = -\varepsilon_o \mu_o \varepsilon_r \mu_r \frac{\partial^2 E}{\partial t^2} \tag{2.8}$$

If we ignored the losses, then μ_r and ε_r are considered as real numbers. One can notice from the above equation that the wave equation is not changed when we change the signs of ε_r and μ_r simultaneously. To undoubtedly comprehend why such materials are termed left-handed materials, let's suppose a time-harmonic and plane-wave variation for fields in the Maxwell's equations.

$$\mathrm{E}(x, y, z, t) = E e^{i\omega t - ik.r} \tag{2.9}$$

Here k is the wave vector. Same equation can be written for *H*. Then Maxwell's equations acquire the form:

$$k \times E = -\omega \mu_O \mu_r \mathrm{H} \tag{2.10}$$

$$k \times H = +\omega \varepsilon_o \varepsilon_r \mathrm{E} \tag{2.11}$$

Since the equations 2.10 and 2.11, and the definition of cross product, we can see that for $\varepsilon_r > 0$ and $\mu_r > 0$ the vectors *H, E* and k form the right-handed thumb rule of vectors and if $\varepsilon_r < 0$ and $\mu_r < 0$ then the vectors form the left-handed triplets. It is clear that when a medium has negative permeability and negative permittivity, then the phase velocity will be anti-parallel to the direction of wave propagation or the direction in which the energy flow. Thus we can say that the medium has also negative phase velocity. Even though the direction of energy is propagated from the transmitter to the receiver, the phase travels in the reverse direction and is shown in fig.2.2

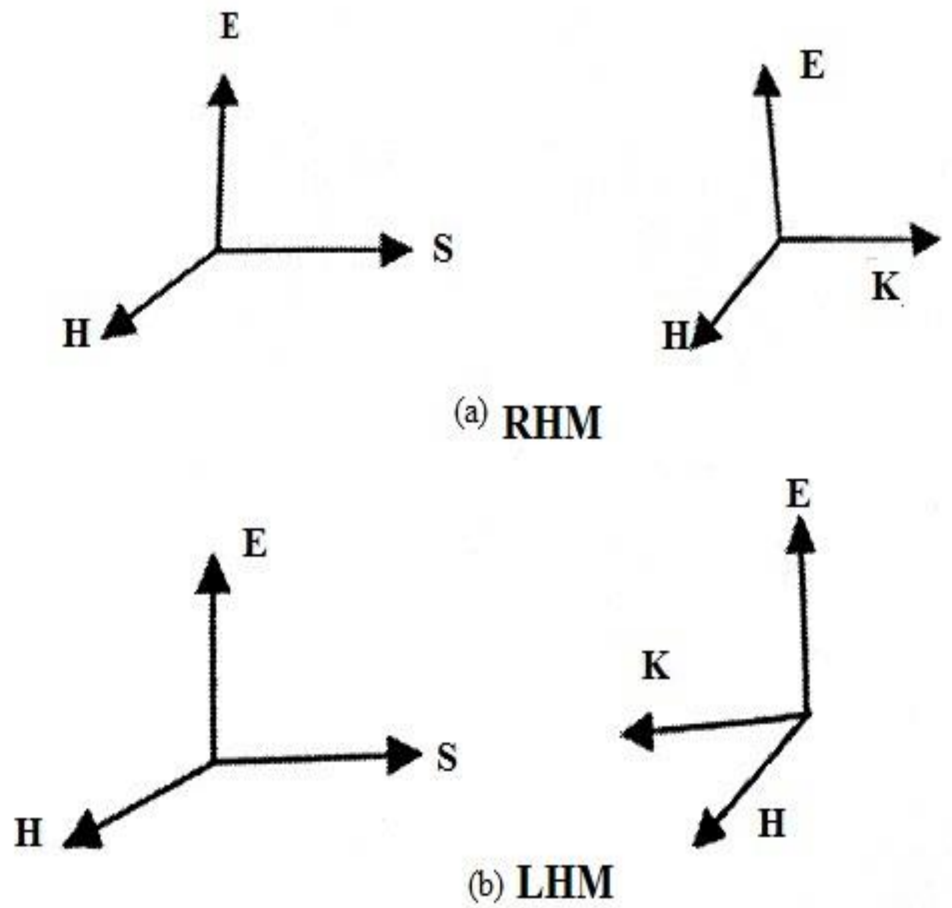


Fig.2.2 Propagation of wave in RH and LH medium.

As we know that the that the index of refraction of any material can be by the square root of the product of its relative permittivity and relative permeability and is given by the equation below:

$$n = \pm\sqrt{\varepsilon\mu} \tag{2.12}$$

Here n represents a refractive index of material and ε is permittivity and μ represents a permeability of the material.

From above equation it seems that negative permeability and permittivity won't offer ascent to negative refractive index medium. However negative index of refraction is due to the square root of the product and has been proved by Ziotlkowski [6] that the square root of the product of the permeability and the permittivity is correct and give rise to the negative refractive index. The mathematical proof is given below:

$$k = \omega\sqrt{\mu\varepsilon} = k_o n \tag{2.13}$$

Where k is the wave number.

$$k_{o=} \omega\sqrt{\varepsilon_o\mu_o} \tag{2.14}$$

$$n = \pm\sqrt{\mu_r\varepsilon_r} \tag{2.15}$$

$$\vartheta = \frac{\omega}{k} = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{\mu_r\varepsilon_r}\sqrt{\mu_o\varepsilon_o}} = \frac{c}{\sqrt{\mu_r\varepsilon_r}} = \frac{c}{n} \tag{2.16}$$

$$z = \frac{H_o}{E_o} = \frac{k}{\omega\varepsilon} = \sqrt{\frac{\mu}{\varepsilon}} = \xi \tag{2.17}$$

Here we observe that the refractive index 'n' is positive even though μ and ε are being negative. But for the double negative material (DNG), the refractive index is negative and can be proved when the permeability and the permittivity of the medium are calculated in form of magnitude and phase as:

$$\varepsilon_r = |\varepsilon_r|e^{j\emptyset_\varepsilon} \text{, where } \emptyset_\varepsilon = \left(\frac{\pi}{2}, \pi\right) \tag{2.18}$$

$$\mu_r = |\mu_r|e^{j\emptyset_\mu} \text{, where } \emptyset_\mu = \left(\frac{\pi}{2}, \pi\right) \tag{2.19}$$

Then the refractive index and the wave impedance of the medium can be written as:

$$n = \sqrt{|\mu_r\varepsilon_r|}\, e^{j\emptyset_n} \tag{2.20}$$

$$\xi = \sqrt{\left|\frac{\mu_r}{\varepsilon_r}\right|}\, e^{j\emptyset_\xi} \tag{2.21}$$

Regardless of the choice of the root, the refractive index for the medium turns out to be negative. By substituting the negative refractive index in the wave equation, we find that the poynting vector and the wave vector for a wave of this type of medium will be anti-parallel and hence will be exhibiting left-handed properties. In this medium the refractive index is negative and the wave travelling from the air into the medium will bend towards the similar region of the normal as the incident ray. This phenomenon is illustrated below:

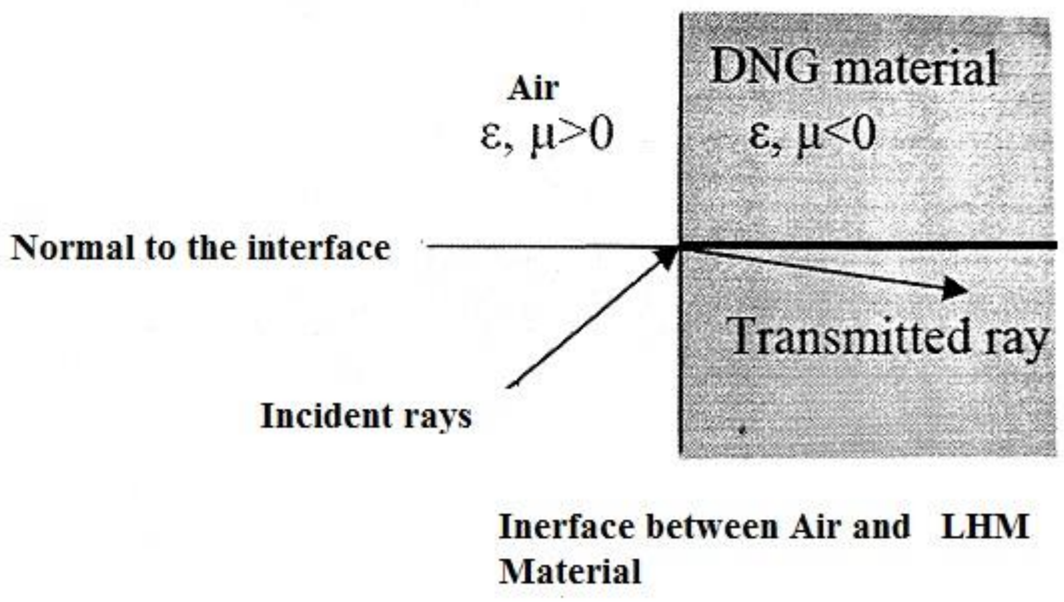


Fig.2.3 Refraction at DPS-DNG.

So material can be classified on the basis of μ and ε as given in the figure below:

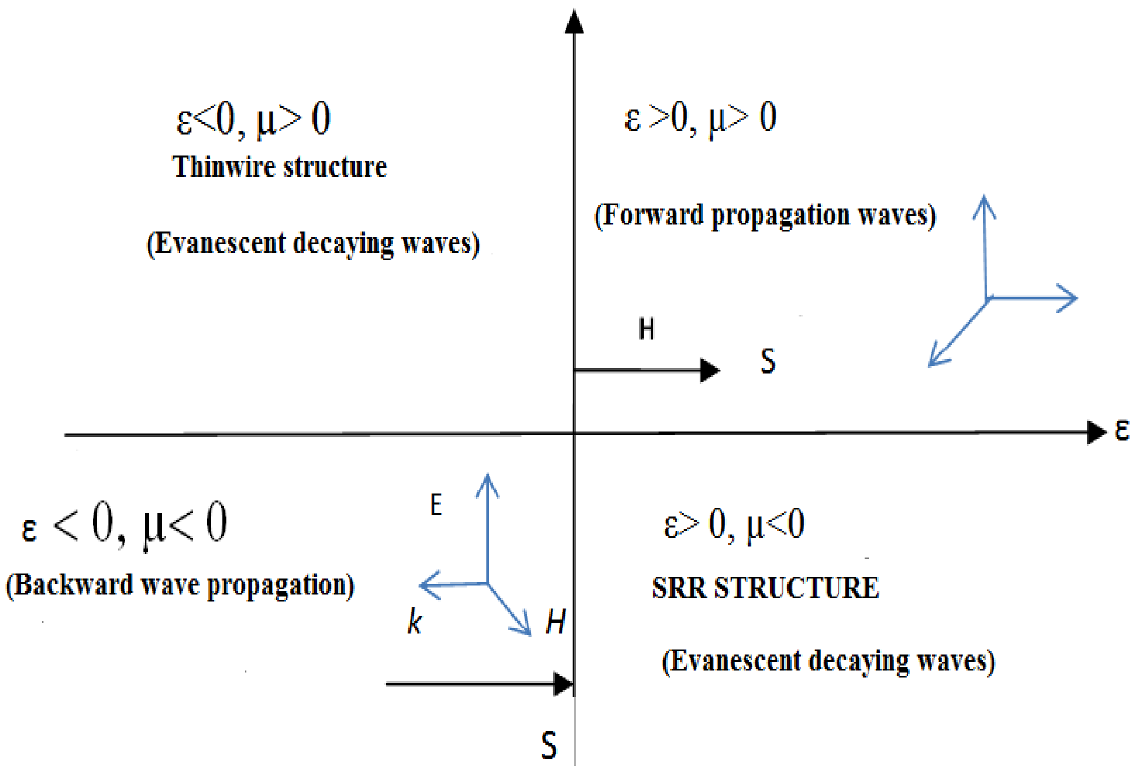


Fig.2.4 classification of material on the basis of μ and ε.

From Fig.2.4, in first quadrant, the wave travelling from air into the medium (plasmas, ferrites) it gets reflected so the wave attenuates. But in the case of MTMs and the conventional materials, negative and positive refraction take place respectively and wave propagates [7].

In the first quadrant ($\varepsilon > 0, \mu > 0$) which represents the right-handed material (RHM). The wave propagates in the forward direction in the first quadrant. It is the most commonly used material. It is the conventional material which follows the right hand thumb rule.

In the second quadrant ($\varepsilon < 0, \mu > 0$) .This quadrant is also known as epsilon negative material (ENM). It explains the electric plasmas which support the evanescent waves.

In the fourth quadrant ($\varepsilon > 0, \mu < 0$) which also supports the evanescent waves. This quadrant is also known as Mu negative material (MNM).

In the third quadrant ($\varepsilon < 0, \mu < 0$) which represents the metamaterials also known as left-handed material (LHM), double negative material (DNG). It follows the left- handed rule because the backward wave propagation takes place in this quadrant. Because of negative permeability and permittivity, the refractive index of this medium is calculated to be negative. Therefore this quadrant is also called as negative index material (NIM). Material that comes in quadrant I, II and IV are found in nature, however naturally existing materials with negative permeability and permittivity have not yet discovered. The electromagnetic vector *H*, the electric vector *E* and the wave vector form the left-handed triplets as shown on the figure above.

2.5 BACKWARD WAVES

It can be supposed from the Maxwell's equations that the medium having a negative permeability and permittivity which is also referred as double negative materials (DNGs) as well as left-handed materials (LHMs), which form a LH triad. The LH triad means that the phase velocity will be ant-parallel to the direction of propagation of wave or flow of energy. In another word, the wave has a positive group velocity and negative phase velocity. Even though the direction of wave propagation is always sent from the sender to the receiver, the phase front travels towards the source or in the opposite direction [8]. Therefore the left-handed materials support backward wave. This phenomenon is shown in the figure below:

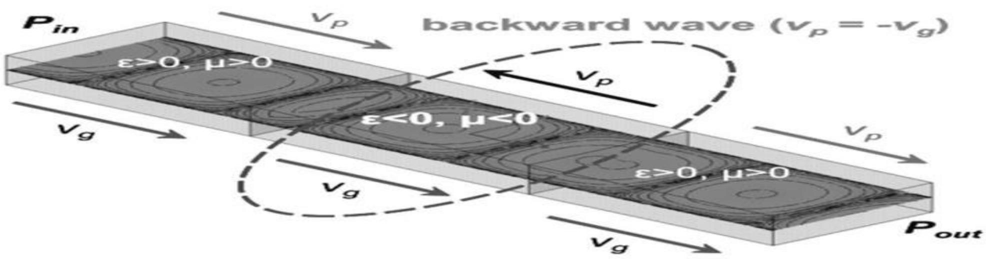


Fig.2.5 Ant- parallel phase and group velocity of MTMs.

2.6 NEGATIVE REFRACTION PHENOMENON

In left-handed material, the wave travelling from air to medium and bend on the similar region of the normal as the incident ray. This phenomenon is known as negative refraction index, which given by the equation 2.12 and is shown in Fig 2.6:

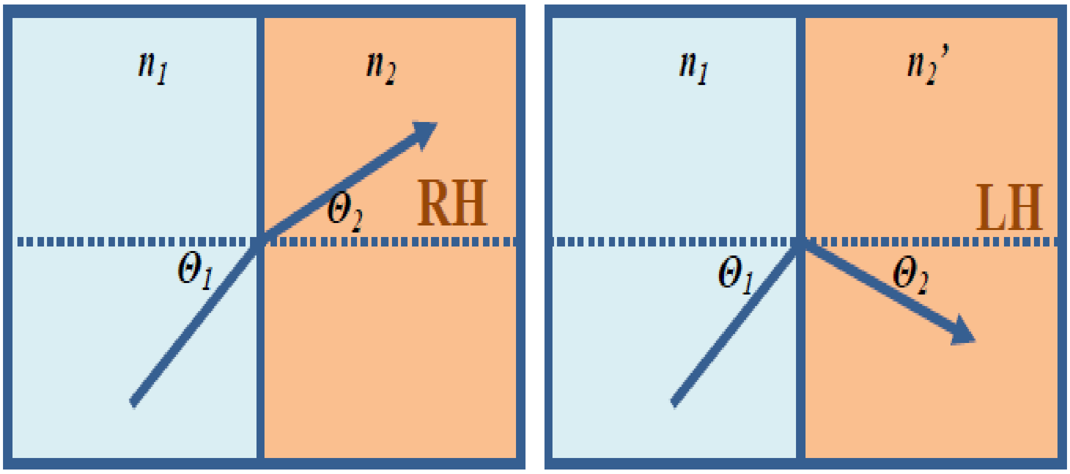


Fig 2.6 the refracted wave in RH and LH medium.

"Metamaterials are artificially designed material with negative permittivity, negative permeability and negative refractive index, which are not available in nature"[9]. Matamaterials have negative refractive index, in which the Snell's law supports the wave propagation that refracted in a wrong way [10]. In short left-handed materials are just opposite to the Snell's law, hence referred as negative refractive index materials. Negative permittivity and negative permeability occur in nature but not simultaneously [11]. When μ_r and ε_r both are negative, then negative index refraction can be obtained, as shown in the following equation below:

$$n = \sqrt{(-\varepsilon_r)(-\mu_r)}$$

$$n = \sqrt{\varepsilon_r (e^{-j\pi}) \mu_r (e^{-j\pi})}$$

$$= \sqrt{\varepsilon_r \mu_r}\,(e^{-j\pi})^{\frac{1}{2}}\,(e^{-j\pi})^{\frac{1}{2}}$$

$$= \sqrt{\varepsilon_r \mu_r}\,(e^{-j\pi/2} e^{-j\pi/2})$$

$$= -1\sqrt{\varepsilon_r \mu_r} < 0 \ldots \qquad \text{(i)}$$

2.7 Some important properties of LHMs.

There are basic important phenomena of double negative medium (DNG) discussed by Veselago in 1967 [1], for instance:

- The propagation of EM waves in the DNG media presents with *E*, *H* and *k* in a LH triad in which *E* and *H* are anti-parallel to *k*.
- The phase in the DNG media propagates away from the source (backward wave) with the phase velocity anti-parallel to the group velocity.
- Because of the negative permittivity and the negative permeability, the refractive index also becomes negative.
- Frequency dependence of the constitutive parameters of the DNG medium as a dispersive medium. In composition materials, the permittivity and the permeability are represented as ε_{eff} and μ_{eff} respectively.

2.8 Realization of Left-Handed Materials

“Metamaterials are artificially engineered materials which are not found in nature”. These materials are realized by placing periodic metallic structure in a dielectric substrate which alters the material parameters, with elements of size less than the wavelength of the incoming electromagnetic waves. It gets its property from the structure rather than directly from its composition. It is specially designed to modify the bulky permittivity and permeability of the medium. LH materials are first practically realized by a scientist Schultz et al. [12] by creating a periodical array of spaced conducting non-magnetic SRRs and an collection of continuous wires/posts that showed negative permittivity ε_{eff} and negative permeability μ_{eff} respectively in a certain range of microwave frequencies. Some attempts were made earlier, before the success of realizing the left-handed materials, to realize the material with negative permittivity by Pendry et al. [13].

A three dimension mesh of conducting wires was employed as a structure, in order to create a negative permittivity so that it can alter the permittivity which supports the substrate. In 1999 Pendry et al. [13] demonstrated that an array of conducting non-magnetic rings can modify the permeability of the host substrate to give a negative effective permeability as a function of frequency. So Schultz et al. [13] combined an array of composite structures of wire and an array of conducting non-magnetic SRRs to get a negative refractive index medium in which bothμ_{eff} and ε_{eff} had a negative value which varied as a function of frequency. Split ring resonator generates a desired relative permeability μ_r and the strip wire generates the negative permittivity [14]. Therefore, the negative material which is frequency dependent with negative μ and ε was realized. This would only be possible under one condition that the size of the unit cell should be considerably smaller than the operating wavelength. Therefore, uniform isotropic alterations of the base material properties are given by these periodic structures. In order to study the actual effective parameters of a homogeneous media, the restrictions of the wave on a unit cell dimension is analyzed.

The combination of the conducting non-magnetic SRR and the wire structure can formed a formula which presented the variation of propagation constant *k* as a function of frequency is given below:

$$k^2 = \frac{(\omega^2 - \omega^2{}_p)(\omega^2 - \omega_b{}^2)}{c^2 - (\omega^2 - \omega_o{}^2)} \tag{2.26}$$

In the above equation the range of *k* is real extends from ω_o to $\omega_b = \frac{\omega_O}{\sqrt{(1-F)}}$

Where F is the fractional area closed by rings and ω_o is the resonant frequency of the ring resonator and ω_b is the plasmonic frequency of ring resonator.

For a typical electromagnetic wave of frequency $'\omega'$, the limitation on the dimension of unit cell structure is given by the equation below [15]:

$$a \ll \frac{2\pi c}{\omega} \quad (2.26)$$

Several experiments were performed to form a theory of field and construct a material base on the composite material concept [16-18]. The concept of composite materials provides a very high degree of freedom to develop the material for numerous applications; various new designs were also discovered for these composite material structures. Different structures were designed like 2-D and 3-D structures and their properties were studied along with their effect on the bulk composite medium were also analyzed based on various important parameters like the arrangement of the structures, the size of the lattice, compositions, material used and the spacing between the structures etc [19].

A generic view of metamaterials which is made up of periodic structures which modify the bulk permeability and permittivity for a composite medium are shown in the figure below:

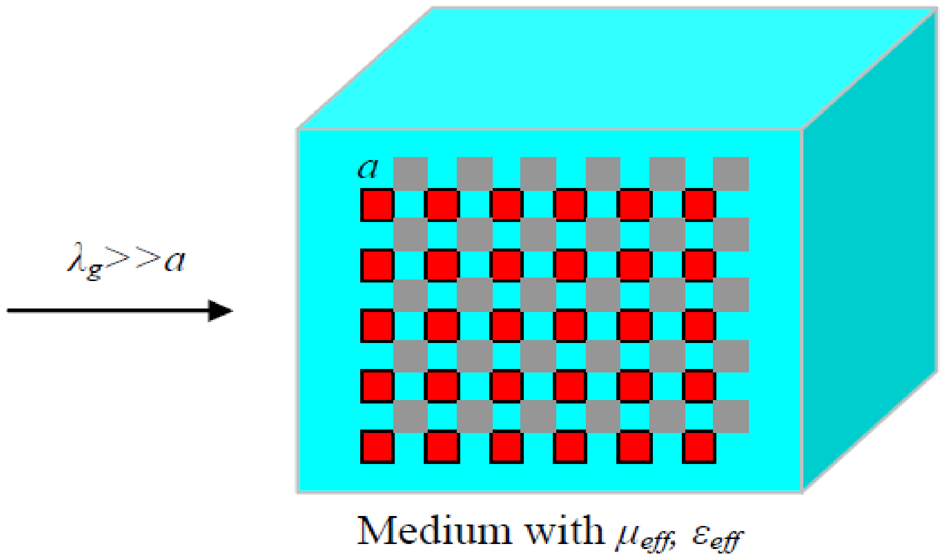


Fig. 2.7 Generic view of a composite medium made of periodic structures consisting of MTMs

(Taken from Ref. [20])

The arrays of the split ring resonators generate a negative permeability and the conducting wire is polarized by electric field and exhibits a desired permittivity for all frequencies below the cut-off frequency.

2.8.1 Metal wire geometry

Thin metallic wires can be utilized to modify the bulky permittivity of the host medium when the medium is excited appropriately with proper boundary conditions. In 1998 Pendry [21] measured the wavelength limit for transverse dielectric of the composite medium made up of long metallic cylinders in a homogeneous medium which is based on photonic gap structures. The geometry of the metal wire which is placed periodically is shown in the figure below:

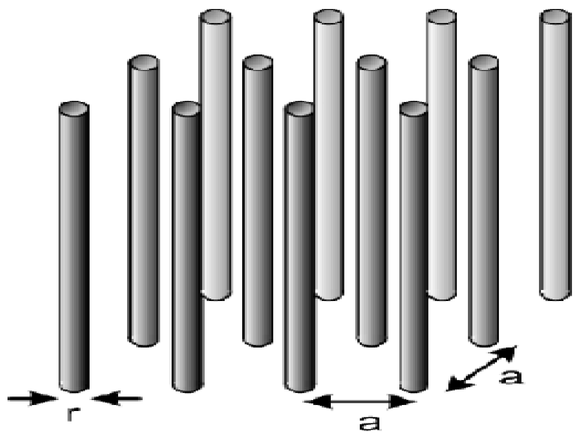


Fig. 2.8 Geometry for a medium with metallic wire strips.

It was studied and then proved that the effective homogeneous medium can be used instead of the composite structure which gives the dispersion relation of the effective permittivity for the composite medium and can be derived from the equation mentioned below [22]:

$$\varepsilon_{eff}(\omega) = \frac{k^2c^2}{\omega^2} \tag{2.27}$$

The effective permittivity can be represented by a Drude dielectric function which changes as a function of frequency and can be controlled by the geometry of the wire. The Drude dielectric function is given by:

$$\varepsilon_{eff}(\omega) = 1 - \frac{{\omega_p}^2}{\omega^2 + j\omega\gamma} \tag{2.28}$$

Where ω_p is the plasma frequency of the metal and γ is the inverse electron relaxation time. The bulk plasma frequency ω_p for the metallic wire structure is given in the equation:

$$ {\omega_p}^2 = \frac{ne^2}{\varepsilon_o m_{eff}} \tag{2.29}$$

Where m_{eff} the effective mass of the electron is, n is the electron density and e is the electron charge and ε_o is the relative permittivity of the free space.

Considering the geometry of the metal wire for calculating the effective permittivity as a function of frequency, the plasma frequency is the most important in the wire structure used in the designing of a composite material is given below:

$$ {\omega_p}^2 = \frac{2\pi {c_o}^2}{a^2 \ln(\frac{a}{r})} \tag{2.29}$$

Where$'a$' is the spacing between the wire strips,$'r$' is the radius of the wire structure and c_o represents the speed of light in free space. In the equation 2.29 the plasma frequency is inversely proportional to the effective mass of wire structure. As decreasing the effective mass make a large shift in the plasma frequency. So to maintain the wire array as a homogeneous material, the radius of the wire strip must keep small as compared to the dimension of lattice.

2.8.2 Split Ring Resonator Geometry

As we already have discussed that split ring resonators are placed in the host medium which is responsible for the generation of negative permeability of the bulk composite medium which is varied as a microwave frequency. This variation of the permeability as a function of frequency gives a negative value in a certain band of frequency. And this negative permeability region is widely observed between the resonant frequencies and the plasma frequency of the SRR. The geometry of the SRR is very simple and has a split in the rings. There are numbers of resonator types which are very import and helpful in the RF and microwave filter purposes. So the split in the rings causes the ring to resonate at very high frequencies which cannot occur in the simple closed ring of the same size and design. In general, a closed ring is a quarter wavelengths in size at its resonant frequency. The best thing about split in the rings is that, it reduces the size to one-tenth of the wavelength and thus makes the rings to resonate at much higher frequency than the closed rings. The rings are prepared of nonmagnetic metal like copper and the split gap between them. Thus the magnetic effect generated by the split ring resonators is increased by the capacitive elements. The splits in the ring structure provides the required capacitive effect in the resonator circuit even though there is not a closed path for the current to flow, however the strong capacitance between the two concentric rings allow the current to flow. Since the split ring resonator structure has a capacitance and inductance in it, the effective permeability shows a resonant form.

The resonant interaction between the capacitance and the inductance in the structure which is due to the gap in the structure arises the resonant frequency. During resonance, the electromagnetic energy is being shared between the magnetic field and the electric field with the inductive and capacitive elements in the structure respectively. This gives an idea that the effective permeability of the structure is above and around the resonant frequency. Above the resonant frequency the split ring resonators show negative and below the resonant frequency it's positive. Typical structures of split-ring resonator are illustrated in the Fig.2.9 below:

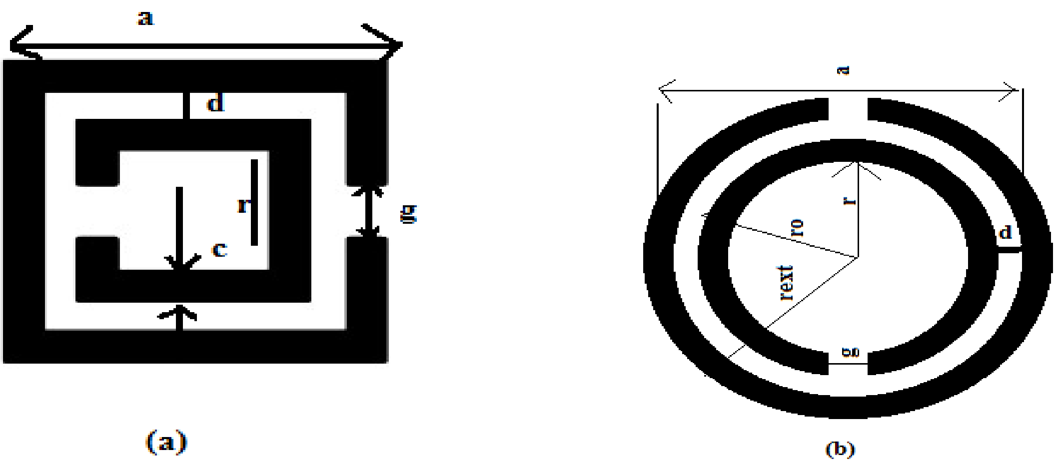


Fig.2.9: SRR geometry. (a)Square SRR.

(b) Circular SRR.

In the square SRR, ‘a’ is the length of the outer-most dimension, r_{ext} is the external radius for a circular SRR. The ‘r_o’ represents an average radius of two concentric rings of the SRR. The width of each ring is separated by ‘c’ and the separation between them is represented by‘d’. The split in the two rings is denoted by ‘g’. The effective permeability ‘μ_{eff}’ of the split-ring resonator can be illustrated by the equation given below:

$$\mu_{eff} = 1 - \frac{F}{1+\frac{j2\sigma}{\omega r\mu_o} - \frac{3}{\pi^2\mu_o\omega^2 Cr^3}} \quad (2.31)$$

Where F is the fractional volume given by the Eq.2.32 of the unit cell which is defined as the area covered by the interior of the concentric rings having a radius ‘r’ and the capacitance ‘C’ to the lattice dimension.

$$F = \frac{\pi r^2}{a} \quad (2.32)$$

The ‘C' is the capacitance of the SRR given by the equation given below:

$$C = \frac{\varepsilon_o}{d} = \frac{1}{dc_o{}^2\mu_o} \quad (2.33)$$

The effective permeability for the structure started to diverge from a particular resonant frequency ‘ω_o’ and is given by the equation below:

$$\omega_o = \sqrt{\frac{3}{\pi^2\mu_o Cr^3}} = \sqrt{\frac{3dc_o{}^2}{\pi^2 r^3}} \quad (2.34)$$

And the plasma frequency for the resonator structure is given by:

$$\omega_p = \sqrt{\frac{3}{\mu_o\pi^2 Cr^3(1-F)}} = \sqrt{\frac{3dc_o{}^2}{\pi^2 r^3(1-\frac{\pi r^2}{a^2}}} \quad (2.35)$$

It can be seen from the above equation that the plasma frequency of the split ring structure depends on the fractional volume not closed in by the inner ring. The dispersion relation of the effective permeability of the split ring resonators has a gap among plasma frequency and the resonant frequency. Also the circular geometries have smaller area than the square one having the same dimension, thus mostly square geometries are used for designing the split ring resonator. A split ring resonator is much better than the conventional microwave resonator as it is capable of resonating with much smaller size and has low radiation losses and high quality factors. This split ring resonator is used in designing a composite medium which exhibits the property of left-handed materials and has a negative index refraction region which changes as a function of frequency. The layout and the equivalent circuit is given in figure below:

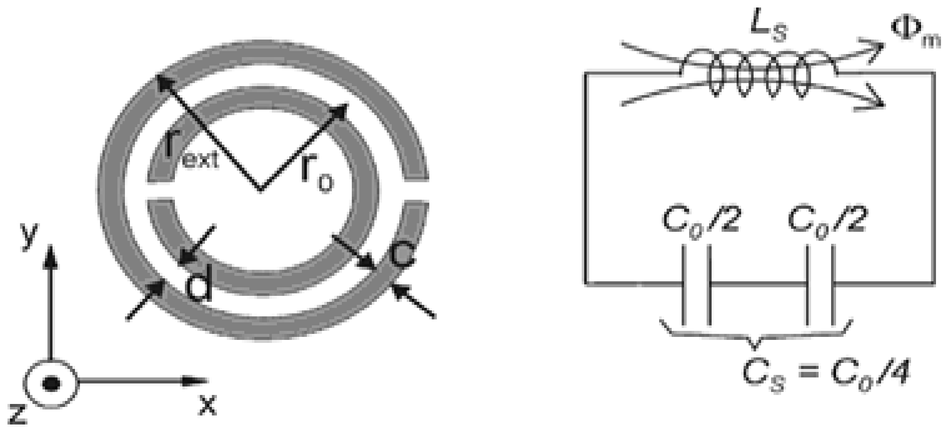


Fig.2.10 Layout of SRR and its equivalent circuit

The split ring resonator acts as a LC resonator and is used to propose in the form of equivalent-circuit as shown in the Fig.2.10 [23]. In the fig.2.9 $C_{o=}\ 2\pi r_o C_p$ and C_o is the overall capacitance between the rings and C_p is the per unit length capacitance among the rings. In addition, the resonance frequency can be denoted by $f_o = (\ L_s C_s)^{-\frac{1}{2}}$ and this C_s is the series capacitance of the upper and lower halves of the split ring resonator. There are different kinds of SRR that has been future so far, for example double split rings, single split rings, nested split rings, rod split rings, spiral split rings and the extended S structure and so on [24]. There are also different types of split ring resonator in the double ring structure and each ring has a gap [25]. A split ring structure can be created by using concentric circular rings, or else can be fashioned by two square rings one inside another [25].

2.8.3 Composite DNG using split ring resonators and wire structures

Double negative materials can be proposed by using SRR with the Metal wire structures in a lattice design which shows negative index refraction. The implemented unit cell structure is shown in Fig.2.11 which exhibits a double negative medium. While designing the split ring resonator in the unit cell of the MTMs structure is placed are etched above the substrate in such a way that the magnetic field is parallel to the axis of rings and wire strip is positioned in such a way that the electric field passes along its axis.

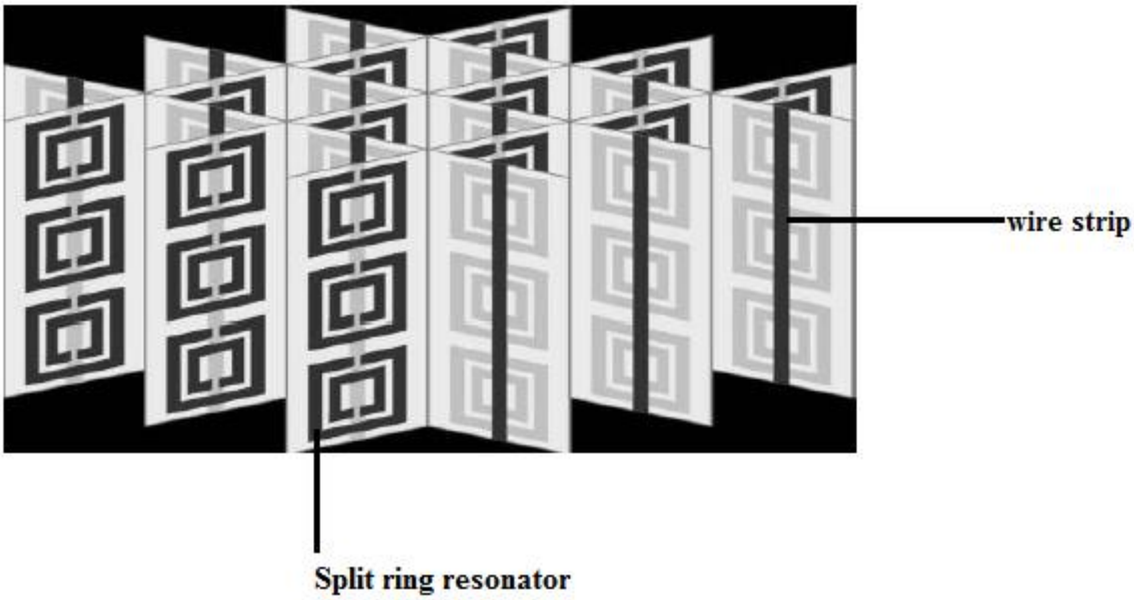


Fig.2.11 Split ring resonator and wire medium.

These composite medium can be designed artificially and can be used for various number of microwave applications such as in designing of microwave filters, super lens, cloaking devices, absorbers, couplers, antennas with the compact size and the enhanced properties.

2.8.4 Complementary Split Ring Resonator

In the year 2004 Falcone et al. introduced the complementary split ring resonators (CSRRs) as novel elements of metamaterial that show negative permittivity [26, 27]. The CSRR, a paired counterpart of SRR which is impressed on the ground plane. Sometimes it is also referred as slotted split-ring resonators are consists of slots which is the same dimension as that of the SRR. It follows the principle of duality, as the properties of CSRRs are in a dual relation of the properties of SRRs. The CSRRs behave as an electric point dipole with negative polarization, whereas SRRs act as a magnetic point dipole. The electric field in the CSRR is kept parallel to plane of CSRR as to create a strong electric dipole which affects the resonant frequency of it [19]. The complete structure of CSRRs and its equivalent circuit is shown in fig.2.10. On comparing the equivalent circuit of the CSRRs with SRRs, it is seen the inductance L_s in the SRR has been replaced by C_c of the disk of radius r_o-$^{c}/_{2}$ bounded by ground plane of c distance from its edge. In addition the two capacitances $\frac{C_o}{2}$ connected in series in the SRR are substituted by two inductances which are connected in parallel in the CSRRs circuit model is connected between the inner disk the ground [12]. Each one of the inductance is given by $\frac{L_o}{2}$ and $L_o = 2\pi r_o L_P$, here L_p is the per unit length inductance. The first LH line depend on the CSRRs were realized via imprinting series capacitive gaps in the conductor wire strip, over the position taken by the CSRRs [12]. The series gaps generate the negative effective permeability of that particular design structure. Therefore the combination of these two elements, the gaps and CSRRs, a narrow band with negative permittivity and permeability simultaneously showed around the resonant frequency of resonators.

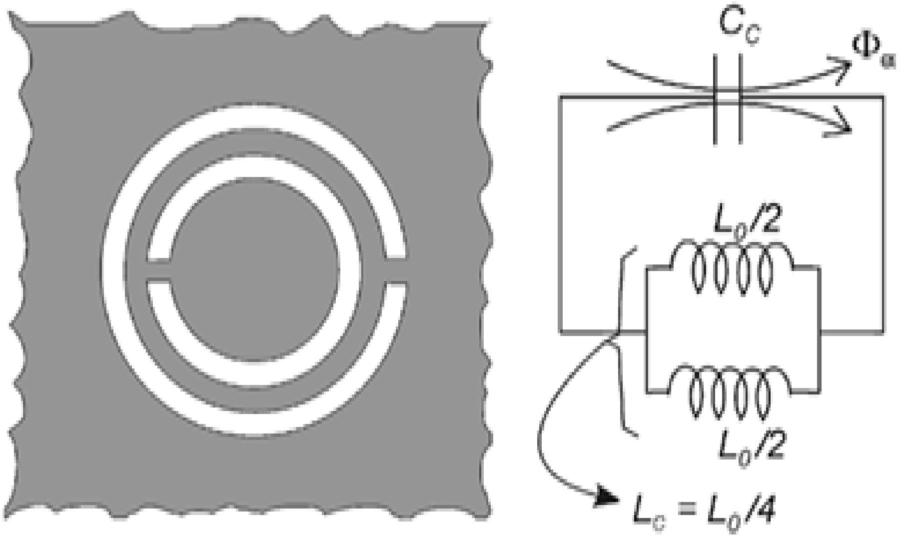


Fig.2.12 Layout of CSRRs and its equivalent circuit model

The double slit SRR has the similar inductance like that of the split ring resonator however its capacitance is four times smaller as it is a result of series connected edge capacitances of each SRR quarter [28]. However, this put emphasis on the fact that the resonance frequency of complementary split ring resonator is double the resonance frequency of SRR and as a result the electrical bulk of the particle cannot be made very small. All these structures are used to design a compact size microwave filter.

CHAPTER-3

METAMATERIAL BASED TRANSMISSION LINES

3.1 INTRODUCTION

Metamaterial based transmission lines are non-natural lines in which the right-left handed composite materials are fixed on the host coplanar waveguides or the transmission lines which are loaded with the reactive elements. A classic understanding of metamaterial lines are found in quasi-lumped transmission line with elementary cells consisting of shunt inductance and series capacitor but the conventional shunt capacitance and the series inductance cannot be circumvent so the concept of the RH handed transmission lines are discovered and based on this idea, a number of applications have been established. Their characteristics are controllable. The TL line approach is used, because the split-ring resonator depends on LH metamaterials shows LH properties around the resonance frequency. Hence the realizations of left-handed materials are called as resonance approach [29]. In the early 2000's, these artificial lines were suggested [4, 30, 31, 32, 33], which are motivated on MTMs which shows analogous properties, and in some case manufactures utilizing the same essential particles [34, 35].

The characteristics of the MTM-TLs are controllable. Moreover these non-natural lines can be engineered to show LH wave propagation in a particular range of frequencies. The semi-lumped and reactive elements which are used in the implementation in these lines are electrically small, so the conditions to attain homogeneity can also be accomplished and that is a small period as compared to signal wavelength. Under these conditions, the effective parameters μ_{eff} and ε_{eff} are studied. Though homogeneity is not only the primary requisite in transmission lines. Undeniably homogeneity can only be attained in a particular area of the approved band [4].

In microwave engineering applications, the resonance approach isn't pragmatic in many cases, such as it is bulky and not valid to planar microwave circuits, it gives narrow band because of the prerequisite of operation near split-ring resonator resonance, and lossy owing to condition of process around split-ring resonator resonance. So to solve these issues of SRR based LH metamaterials for microwave engineering applications researchers discovered that backward wave transmission line can be developed to realize non resonant LH metamaterials.

From the microwave circuit design point of view, the advantages of MTM-TLs depend on miniaturization and on the possibility to control the dispersion diagram and characteristic impedance, rather than on homogeneity. Thus metamaterial transmission lines are engineered lines, consisting on a host loaded with semi-lumped and reactive elements with controllable characteristics. Homogenity isn't the important requirement for these lines. [36, 37].

This TL approach to left-handed materials depending on the double composition of left-handed and usual transmission lines. The model of conventional transmission loaded with series inductance (LR) and shunt capacitance (CR) whereas the left-handed transmission loaded with series capacitance (CL) and shunt inductance (LL) are illustrated below:

(a) Conventional (RH) transmission line. (b) LH transmission line unit cell.

Fig.3.1Transmission line circuit model unit cell.

The propagation constant of the LH and RH transmissions are given by:

$$\beta_{RH} = \omega\sqrt{C_R L_R} \quad …….. \qquad \text{(i)}$$

$$\beta_{LH} = \omega\sqrt{C_L L_L} \quad …… \qquad \text{(ii)}$$

By plotting the dispersion diagram between ω-β, the phase velocity ($v_{p=\frac{\omega}{\beta}}$) and the group velocity ($v_{g\,=\,d\omega/_{d\beta}}$) of metamaterial can examined directly. The ω-β diagram [8] for the unit cell are plotted in the figure below:

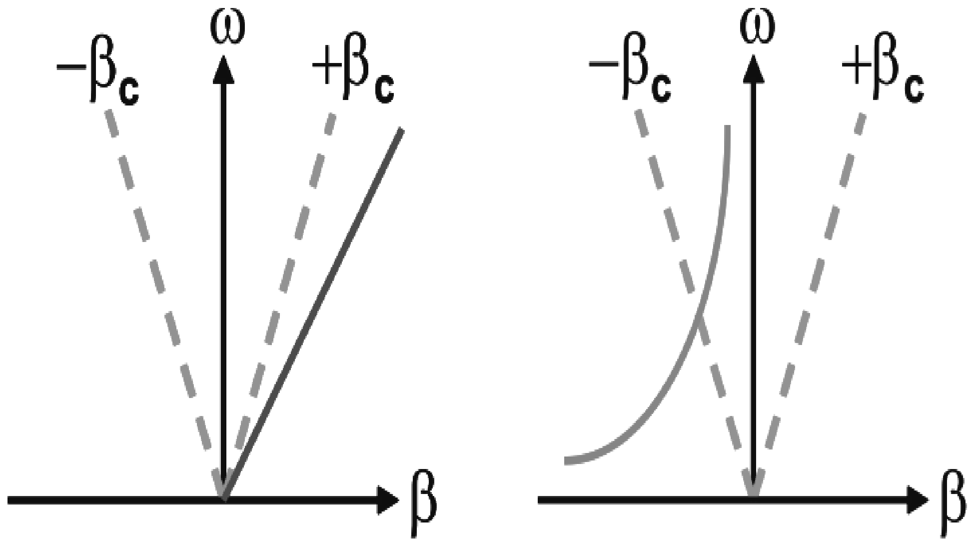


Fig.3.2 Dispersion diagram of unit cell

In the above figure it is observed that the v_p and v_g for RH transmission line parallel whereas for LH transmission line the phase velocity and the group velocity are anti-parallel. For that reason the RH transmission supports forward wave propagation while LH transmission supports backward wave propagation. Also the dispersion diagram of LH transmission line shows that the group velocity approaches infinity as increases. The pure LH transmission line is not possible as it disobeys Einstein's special theory of relativity.

3.2 COMPOSITE RIGHT AND LEFT-HANDED TRANSMISSION LINES

Planar left-handed materials can also be realized by using composite right and left-handed transmission lines. A pure transmission line cannot be implemented due to the RH parasitic effects [30]. As a result, a general model of a composite right-left handed transmission is a left-handed transmission line which also contains right-handed characteristics. The general model of a composite right –left handed transmission lines (CRLH-TLs) is illustrated in the Fig.2.11 below and it comprises of a series LH capacitance CL, a series RH inductance LR, and a shunt inductance LL. The propagation constant of a CRLH unit cell is given below:

$$\beta_{CRLH} = S(\omega)\sqrt{\omega^2 L_R C_R + \frac{1}{\omega^2 L_L C_L} - \left(\frac{L_R}{L_L} + \frac{C_R}{L_R}\right)} \ldots\ldots \quad \text{(iii)}$$

Where $S(\omega) = -1 \;\; if \qquad \omega < \omega\Gamma 1 = \min\left(\frac{1}{\sqrt{L_R C_R}}, \frac{1}{\sqrt{L_L C_R}}\right)$

$$S(\omega) = +1 \;\; if \qquad \omega > \omega\Gamma 2 = \max\left(\frac{1}{\sqrt{L_R C_L}}, \frac{1}{\sqrt{L_L C_R}}\right)$$

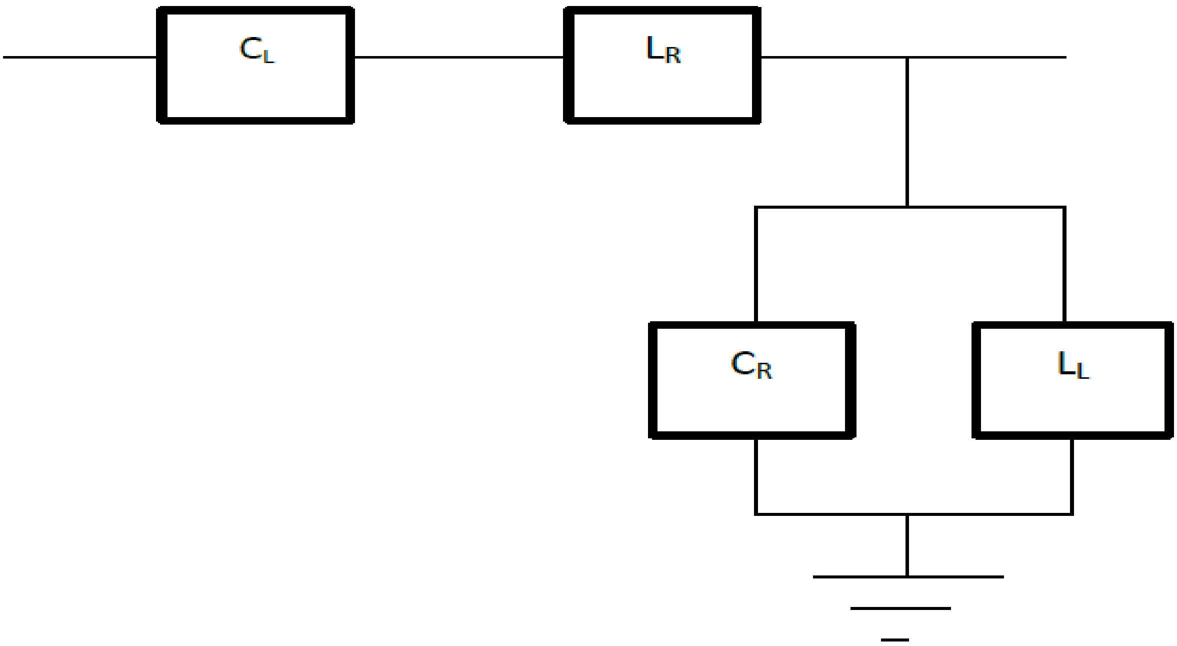
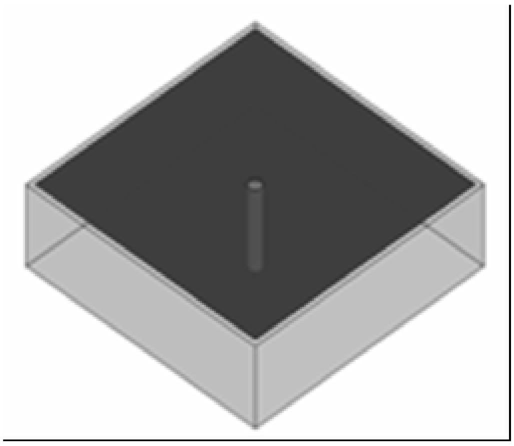


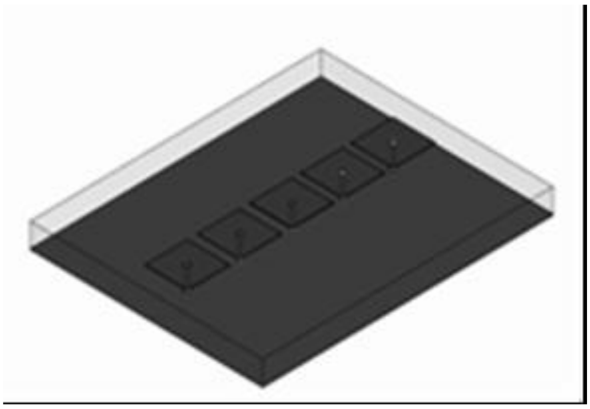
Fig.3.3 The general model of CRLH-TL

3.2.1 Transmission Line Approach CRLH Unit Cell

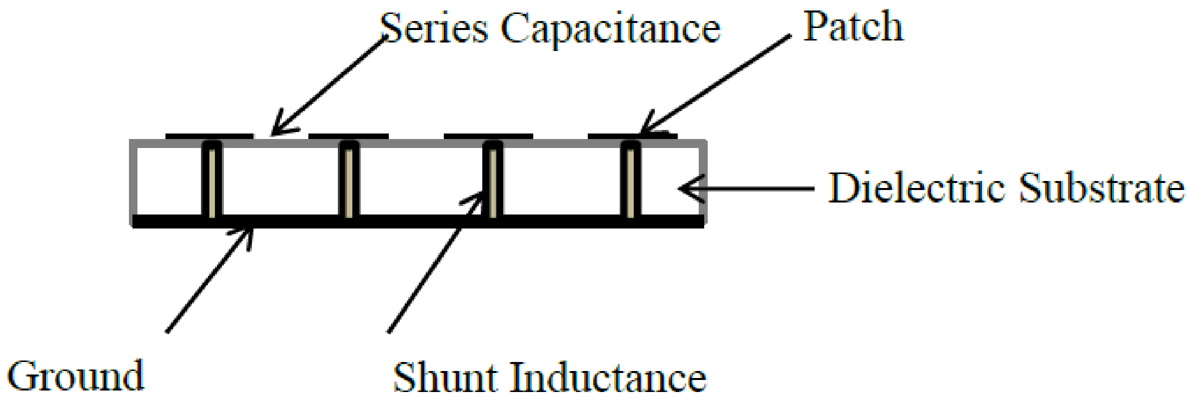
A CRLH unit cell [8] is an arrangement through cylindrical metal usually of perfect conductor and microstrip gaps whose behaviour is equal to arrangement of shunt inductors and series capacitors in that order. This is used to understand metamaterial and this is referred to as TL approach to realize MTM. Metamaterial with unit cell is known as transmission line approach. It is prepared by series capacitance and shunt inductance. The via is applied to inject the ground plane and the patch acts like a shunt inductor and the gaps acts like a series capacitors cab able to achieve by gaps constructed by the free patches.



(a) Using in a Unit Cell



(b) Unit Cell by cascaded



(a) Side View of the Cascaded Unit Cells

Fig.3.4 Geometry of CRLH Unit Cell.

CHAPTER-4

FILTER THEORY

4. 1 INTRODUCTION

The developments in wireless technology have commanded the necessity of new designs of filters [38]. So this wireless communication has been an imperative in human's life from the past few decades. Due to the fastest development in the communication technologies, there have been so many scholars to increase the devices and circuits for its application in multiple frequency bands [39-43]. As well as the necessity of reducing the interference between the channels must be done for all the wireless communication system. Microwave filter is a crucial component to get free from the unnecessary signals from the system and permit the signal in precise frequency to pass through. Planar filters are commonly used because of the low profile, easy in manufacturing and also easy to apply with microwave integrated circuits.

It is very important to design a compact size filters with high frequency selectivity and high rejection at the band boundaries. To achieve these requirements, various design techniques have been accounted [44-47]. As resonators are the building blocks or the basic elements of planar filters and from the outlook of this filter design section, filter designed using complementary split-ring resonators have been established to achieve above requirements [48-50]. CSRRs on microstrip line with a series gap correspond to a pass band frequency [51].

4.2 Definitions and Fundamentals of Filters

As mention above, Filters are the most important part in radio transmitter and receiver systems for the improvement of signals. In other words it can be termed as a transducer for separating waves on the basis of their frequencies. There are main three types of filters which are Passive filter which doesn't require any external source for operating, and the second one is Active filter which depends upon the external source for operating. The lumped elements and the two-port network are used to distribute filters and their frequency responses [38, 53, and 54].

4.2.1 Two-Port Network

The Microwave and the RF components can be expressed by a two-port network which is illustrated in the Fig 3.1 below. A variety of methods have been applied to analyze the two-port network such as; S-parameters, network variables and short-circuit admittance parameters, open-circuit impedance parameters, and the ABCD parameters. These parameters can be changed into one another. The S-parameters are used in this part which consists of the following:

- The Forward Transmission (insertion) gain with the output port ended by a matched load or S_{21} (insertion loss).
- "The Input Reflection coefficient with the output port which is terminated by a matched load or S_{11} (Return Loss)".
- "The reverse transmission gain (insertion) with the input port which is terminated by a matched load or S_{12}".
- "The output reflection coefficient with the input port which is terminated by a matched load" or $S_{22.}$

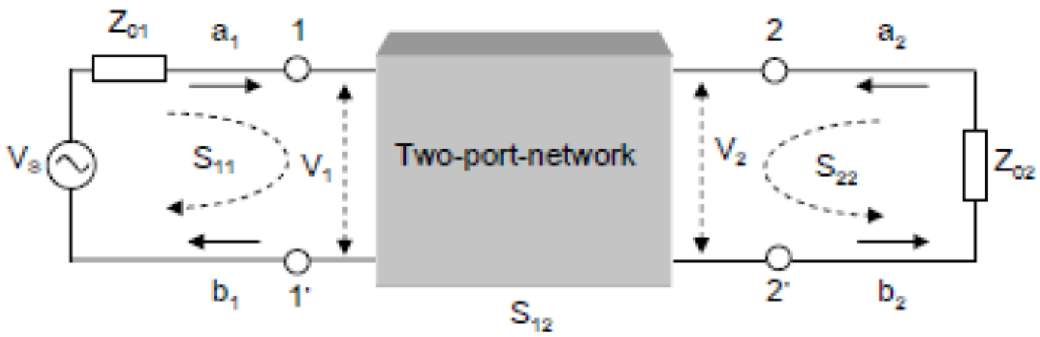


Fig.4.1 Two-port Network with S_{11} and S_{22}

The two-port network given in the above figure has parameters I_1, I_2 and V_1, V_2 which are current variables in complex amplitude at port 1 and port 2 and Z_{01} and Z_{02} are the terminal impedances and V_s is the voltage source.

The sinusoidal voltage at Port 1 is given by:

$$V_1(\mathrm{t}) = |V_1|\cos(\omega t + \emptyset) = |V_1|e^{j(\omega t+\emptyset)} \quad (4.1)$$

Hence, the complex amplitude is given by:

$$V_1 = |V_1|e^{j\emptyset} \quad (4.2)$$

The variables of wave a_1, b_1 and a_2, b_2 are established to simplify the voltage and current of the two-port network where a denotes the incident wave and b denotes reflected waves. Therefore the voltage and current are given by the equations below:

$$V_n = \sqrt{Z_{0n}}(a_n + b_n) \quad \text{and} \quad I_n = \frac{1}{\sqrt{Z_{0n}}}(a_n - b_n), \text{ n=1 and 2} \quad (4.3)$$

$$a_n = \frac{1}{2}\left(\frac{V_n}{\sqrt{Z_{0n}}} + \sqrt{z_{0n}}I_n\right) \text{ and } b_n = \frac{1}{2}\left(\frac{V_n}{\sqrt{Z_{0n}}} - \sqrt{Z_{on}}I_n\right), \text{ n=1and 2} \quad (4.4)$$

The S-parameters of the two-port network in the forms of wave variables are:

$$S_{11} = \frac{a_1}{b_1}\bigg|_{a_{2=0}} \qquad S_{12} = \frac{b_1}{a_2}\bigg|_{a_{1=0}}$$

$$(4.5)$$

$$S_{21} = \frac{b_2}{a_1}\bigg|_{b_{1=0}} \qquad S_{22} = \frac{b_2}{a_2}\bigg|_{a_{1=0}}$$

When a_n = 0, there will not be a wave reflection at Port n in the case of balanced impedance, the matrix form is:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad (4.6)$$

Where S_{11} and S_{22} are both the reflection coefficient, and S_{12} and S_{21} are forward and reverse insertion loss respectively. The above parameters are used to study the components in the microwave frequency.

The phase and the amplitude are denoted by:

$$S_{xy} = |S_{xy}|e^{j\phi_{xy}} \text{ here x and y are the integers 1, 2….} \quad (4.7)$$

The amplitude is always considered in dB from 20log$|S_{xy}|$

As the insertion loss (L_A) and the return loss (L_R) between the port x and y is given by:

$$L_A = -20\log|S_{xy}| \ldots x \neq y \quad (4.8)$$

$$L_R = 20\log|S_{xy}| \quad (4.9)$$

Here the return loss which is proportionally related to the Voltage Standing Wave Ratio by:

$$VSWR = \frac{1+|S_{xy}|}{1-|S_{xy}|} \quad (4.10)$$

These scattering parameters are used in microwave filter designs. In two-port network, the reflection coefficient can be considered in the form of the terminated impedance (Z_{01}) by exchanging with $Z_{in1} = V_1/I_1$. Z_{in1} is known as input impedance by looking at port 1, followed by:

$$S_{11} = \frac{b_1}{a_1}\Big|_{a_2=0} = \frac{V_1/\sqrt{Z_{01}} - I_1\sqrt{Z_{01}}}{V_1/\sqrt{Z_{01}} + I_1\sqrt{Z_{01}}} \quad (4.11)$$

V_1 is substituted by $z_{in1}I_1$, then the reflection coefficient becomes:

$$S_{11} = \frac{Z_{in1}-Z_{01}}{Z_{in1}+Z_{01}} \quad (4.12)$$

Like the above, in this case if we consider the port 2 as the input then $Z_{in2} = V_2/I_2$, here Z_{in2} is the input impedance looking into the port 2. The reflection coefficient becomes:

$$S_{22} = \frac{Z_{in2}-Z_{02}}{Z_{in2}+Z_{02}} \quad (4.13)$$

The S-parameters in the balanced network are:

$$Z_{12} = Z_{21} \text{ and } Z_{11} = Z_{22} \tag{4.14}$$

In the passive and lossless network, the entire input power is from the transmission power and the reflection power:

$$S_{21}S_{21}^{*} + S_{11}S_{11}^{*} = 1 \text{ or } |S_{21}|^2 + |S_{11}|^2 \tag{4.15}$$

4.3 RF and Microwave Filter Characteristics

In passive microwave and RF filters, the lumped components, for example capacitors and inductors are generally utilized to design an RF filter [39]. However, the distributed components like the transmission lines which include the combine line or coupled line and inter-digital structure are another different method to design RF filter. The characteristics of the microwave filters such as low pass, band pass, high pass, band pass and band stop and some particular functions such as Chebychew, Butterworth, Elliptical and Bassel are illustrated by their output response and some important parameters which are shown in the figure below:

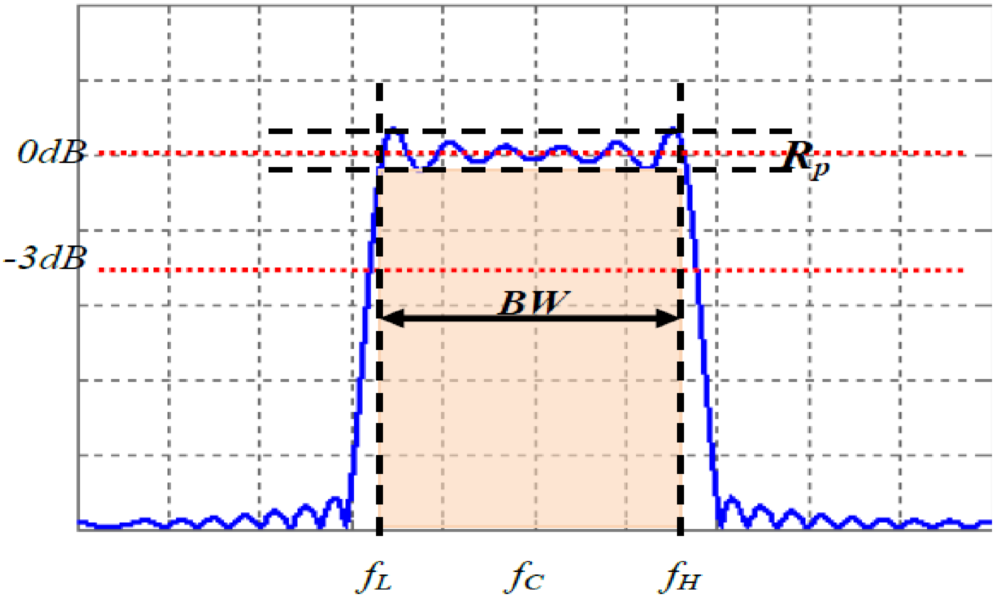


Fig.4.2 The transfer function of Band pass filter

- Ripple (R_P): ripple in the frequency domain is the periodic deviation in the insertion loss, in another word it can be called as the difference between minimum and maximum of the insertion loss in the pass band .
- Bandwidth (BW) or the half-power bandwidth: It is the difference between the lower and the upper frequency of the filter at which the amplitude is 3dB under the pass band response.

  The bandwidth divided by its centre frequency is known as the fractional bandwidth of a filter,$BW/_{f_c}$.
- Insertion Loss (IL): The insertion loss is the signal loss in power while transmitting from one device to another, generally presented in dB as 20log ($^{P_T}/_{P_R}$), where P_T is the power transmitted at the beginning in the load and P_R is the power received by the load. The insertion loss (IL) in the scattering parameter is defined as $IL = -20\log|S_{12}|$dB
- Return Loss (RL): The return loss is the loss of power in the signal reflected measured at the output of the filter.
- Selectivity: selectivity is the required attenuation of the unnecessary frequencies. In filter design, the selectivity of the filter is defined by how much the filter will reject the undesired frequencies.
- Group Delay: it is the amount of time required for signal to pass through the filter. In most of the filter group delay is given by $d\emptyset/df$ which varies with the frequency.
- Q factor: it is the inverse of fractional bandwidth denoted by Q=f_c/BW. A low Q factor gives a wide passband while a high Q factor will have a narrow pass band

CHAPTER-5

DESIGNED FILTER

5.1INTRODUCTION

A Microwave filter is a two-port network which helps to direct the frequency response in a particular point in a microwave system by providing transmission of frequency inside the pass band of the filter and attenuation in the stop band of the filter [54] according to the frequency response of the filter, the filter can be categorized as low pass, high pass, band pass, and band stop filters. In this section a low pass filter is design. So low pass filter is one of the most important filters in the microwave system. It allows the lower frequency elements to go into the signal whereas high frequency component is rejected. For different applications, different filters are present there in the microwave system. One of the challenges of the present and future in the microwave communication devices is the miniaturization of the filter. Low pass filters are a lot crucial component in the microwave communication systems and RF circuits. Low pass filter are utilizes in a variety of electronic appliances which separates noise or interference from neighbouring surroundings. There are many conventional methods to develop a low pass filter such as stepped and open stub. The response of such filters, the cut-off or the roll-off is gradual which is not sharp. As a result, the rejection characteristics have some limitations in such conventional low pass filters. By adding up some new segments, the limitations can be improved and the size is increased in the pass band insertion loss. Although, this increasing does not affect the overall structures. So to overcome these problems, a new artificial material is designed which is known as Metamaterials. These metamaterial structures such as SRRs, CSRR, and other structure are used to design the compact microwave components [55] using printed circuit boards and MMIC technologies [56-59].

In this communication a low pass filter is proposed using sun-shaped resonators. The sun-shaped CSRR is etched on the ground plane and the stub on the micro-strip transmission line.

By loading this structure on the ground plane produces a sharp cut-off and good insertion is achieved. So by proper use of substrates with high dielectric constant, the printed filter's size can be decreased extensively, which also provides a compact size [55] micro-strip filters is constantly favoured over lumped filters at higher frequencies and nowadays they are the most important part of all the RF and wireless communications.

The simulation of this filter has been made by using CST Studio Software. It is the foremost edging device for the rapid and precise 3D simulation of high frequency devices and promote leader in Time Domain simulation. It facilitates the speed and correct study of filters, antennas, planar, couplers, and multi-layer structures and Electromagnetic Coupling effects etc.

5.2 Operating Principle and Design

As it is already discussed in the chapter 2 that split-ring resonators are the most important part in the metamaterial to design microwave filters. It has been applied to the fabrication of left-handed met materials and planar circuits are designed by using split-ring resonators. It was first introduced by Pendry et al. that the combination of an array of SRRs can show negative permeability within its resonant frequency. Recently a number of authors have accounted those CSRRs [60] which are the negative image of split ring resonator [61]. It has been illustrated that CSRR is imprinted in the ground plane or in the conductor strip of planar transmission medium which show a negative effective permittivity to the structure within their resonant frequencies. CSRR has been applied successful to the narrow band filters and diplexers with compact dimensions. The benefit of using complementary split ring resonator is that it helps in reducing the size. Because it is etched in the ground plane of a substrate so it does not have the need of any special area. Compared with conventional CSRR, a novel CSRR is proposed in this section which has a low insertion and a low return loss which is less than -10dB in the pass band and this designed filter can be used in wireless communications. The layout of the single circular CSRR and its equivalent circuit is illustrated below:

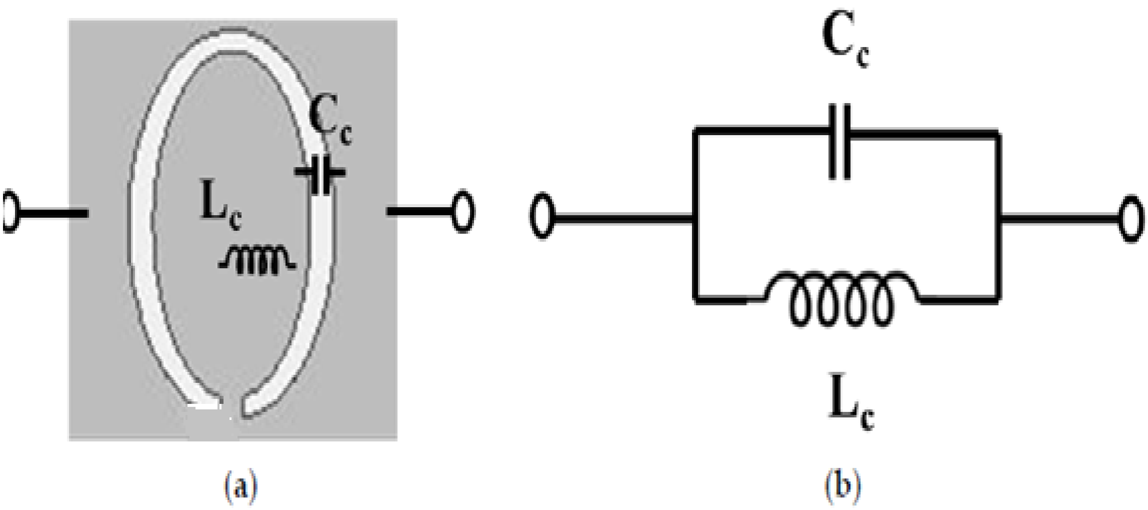


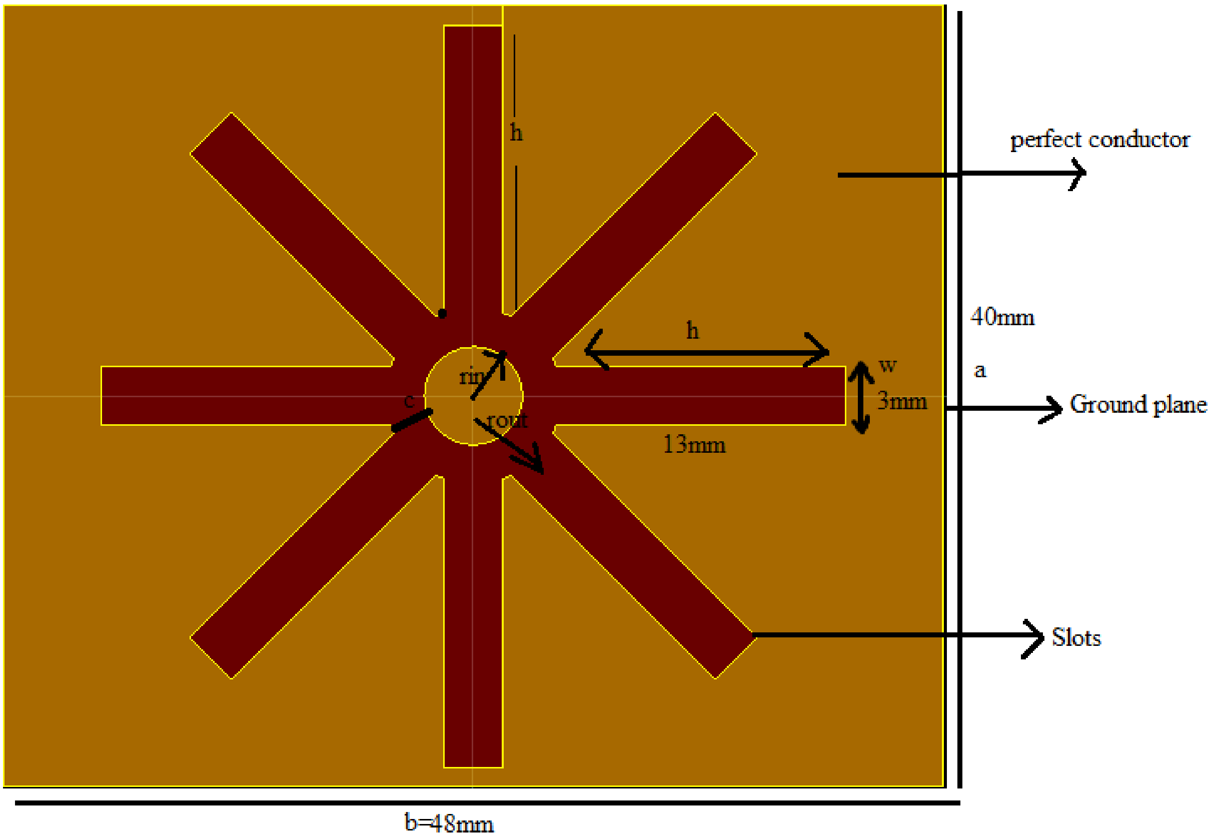
Fig.5.1 (a) Layout and (b) Equivalent circuit model of CSRR

Using this concept a novel sun-shaped LPF is proposed. There are various methods to design a microwave filters. Due to the easy manufacturing, high efficiency, so in this section a sun-shaped low pass filter is designed using a CSRRs and a single stub. This complementary split ring resonator which exhibits a negative permittivity and exhibit the characteristics of left-handed metamaterial are proposed in this section for the designing of low pass filter with great insertion loss and good return loss in pass band. Some of the striking features of the designed CSRRs are their high quality factor, compact size, low radiation loss and low cost of designing in a planar structure [62]. There has been designing and designed many compact filters using the CSRRs with diverse structures being proposed to achieve a wide pass band. Such as stepped impedance resonators, cascading of high pass and low pass CSRR filters [63] and open circuit stub [64] etc. In this proposed work, an improved structure for low pass filter is designed by changing the essential design parameters of the filters.

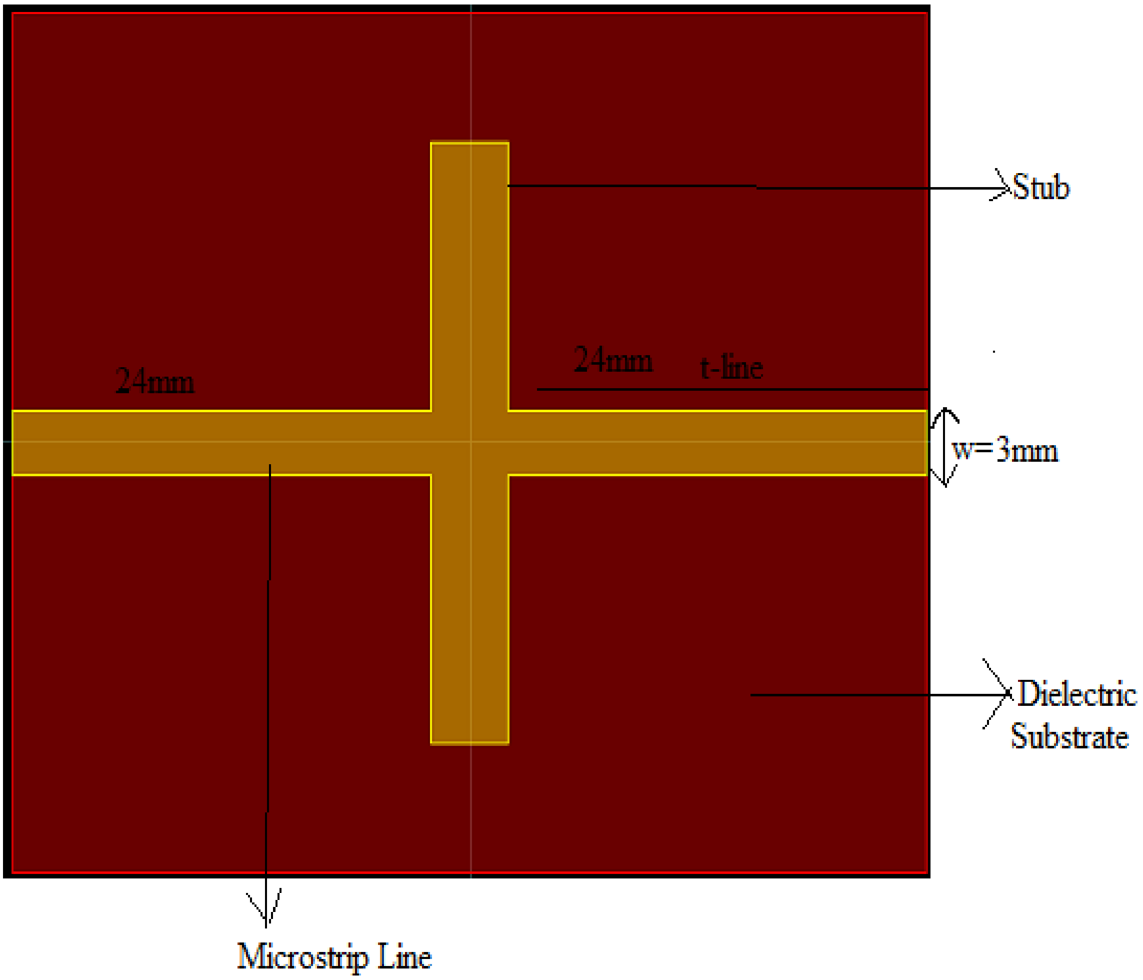
Fig.5.1 shows the design of single circular SRR in which the gap between the inner ring and outer ring is taken as capacitance and patch is taken as inductance. The overall structure act as a LC parallel resonant circuit.

5.3 DESIGN AND SIMULATION

The schematic of the proposed low pass filter with a microstrip transmission line stub on the middle of it and sun-shaped resonator with eight slots on it is on the side of the substrate is shown in Fig.5.2.



(a) Back view of the designed filter



(b) Top view of the designed filter

Fig.5.2 complete geometry of the proposed filter

There are ten design parameters for a low pass filter which controls a resonance frequency of novel filter. The ten parameters important for designing a low pass filter are width of the ring, ring distance between the inner ring and the outer ring, and the width of the eight slots with the ring, and the width of the slots, length of the lots, radius of the inner ring and the outer ring, the capacitance stub, the capacitance stub length, transmission line width and the transmission line length. The resonance frequency can be increased or decreased by changing the dimensions of the designed structure. When the size of the slots increases, the resonance frequency shifts towards the lower frequencies, and when the size of the slots decreases, the resonance frequency shifts towards the higher frequencies.

The sun-shape CSRR LPF is designed on a FR-4 (lossy) substrate having its relative permittivity 'ε_r' equal to 4.30 along with the height of the substrate 'h' equal to 1.6mm. The FR-4 (lossy) substrate was picked. This substrate was picked because of its moderately minimal effort and effortlessly accessible dielectric constant and since it doesn't differ fundamentally with temperature. This substrate has 4.30 dielectric constant. What's more, arrives in an assortment of thicknesses. The ground plane and the transmission line of the filter are made up of copper whose conductivity is equal to 5.8×10^7 S/m and the thickness of the copper is equal to 0.035mm. The design parameters for the low pass filter using sun-shaped resonator is given in the table 5.1 below:

Table 5.1 Design parameters of a CSRR loaded low pass filter.

Parameters for CSRR loaded low pass filter	**Dimensions**
Radius of the outer ring (rout)	4.5mm
Radius of the inner ring (r_{in})	2.5mm
Ring gap	2mm
Transmission line width (t_line_w)	3mm
Transmission line length	24mm
Stub width (stub-w)	4mm
Stub length	28mm
Length of the substrate	48mm
Width of the substrate	40mm
Thickness of the substrate	1.6mm

The transmission line designed has width of 3.00mm in order to have characteristic impedance normalized to 50Ω so that the maximum power is transferred from the waveguide port to the filter. The top view of the low pass filter is shown in the Fig.5.2 (b) containing the transmission line having the gap capacitance and the stub capacitance on it, while the bottom view containing the single circular split ring resonators with eight slots of equal size is imprinted on the ground plane is shown in Fig.5.2 (a).

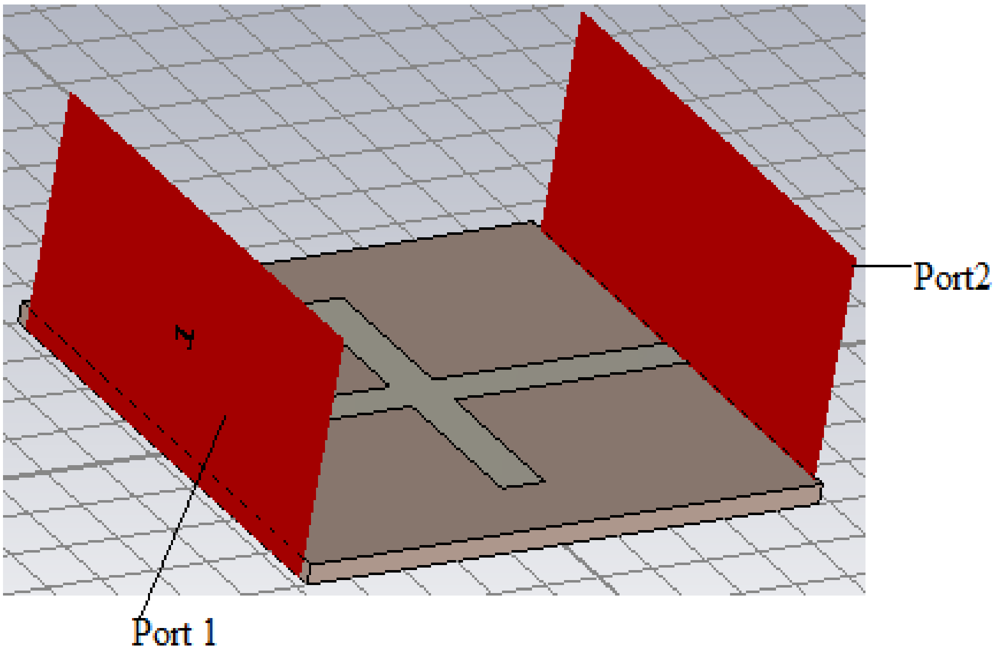


Fig.5.3 the waveguide ports for a microstrip low pass filter.

The low pass filter utilizing this new structure has various interesting highlights, which incorporate the following, such as the stop band is less than -10dB,the structure is very simple, the insertion is very low and to a great degree little component esteems for execution of low-pass filter can be figured it out.

The frequency domain solver is used in CST Microwave Studio for obtaining S-parameters of the designed sun-shaped low pass filter. The Fig.5.4 shows the simulated S_{21} results of the filter.

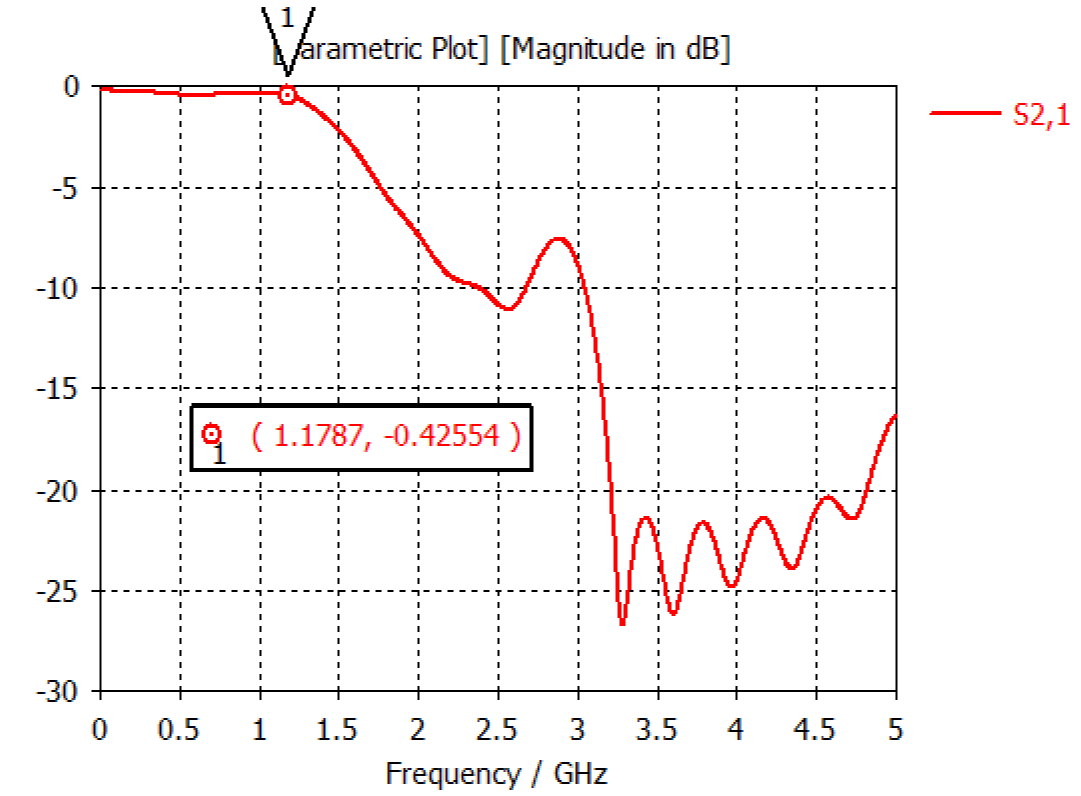


Fig.5.4 S_{21} result of the designed low pass filter.

The S_{21} result which is the transmission coefficient (insertion loss) from port 1 to port 2 of the filter. From the figure above it is seen that the LPF is actually very well behaved, so from 0 to 1.178 GHz the low pass filter is got very low insertion loss and it actually very flat well behaved. It has a low insertion loss of -0.3dBwhich is much closer to zero. This novel filter does not have a ripple and it's a very low loss.

The Fig.5.5 shows the simulated S_{11} result of the filter.

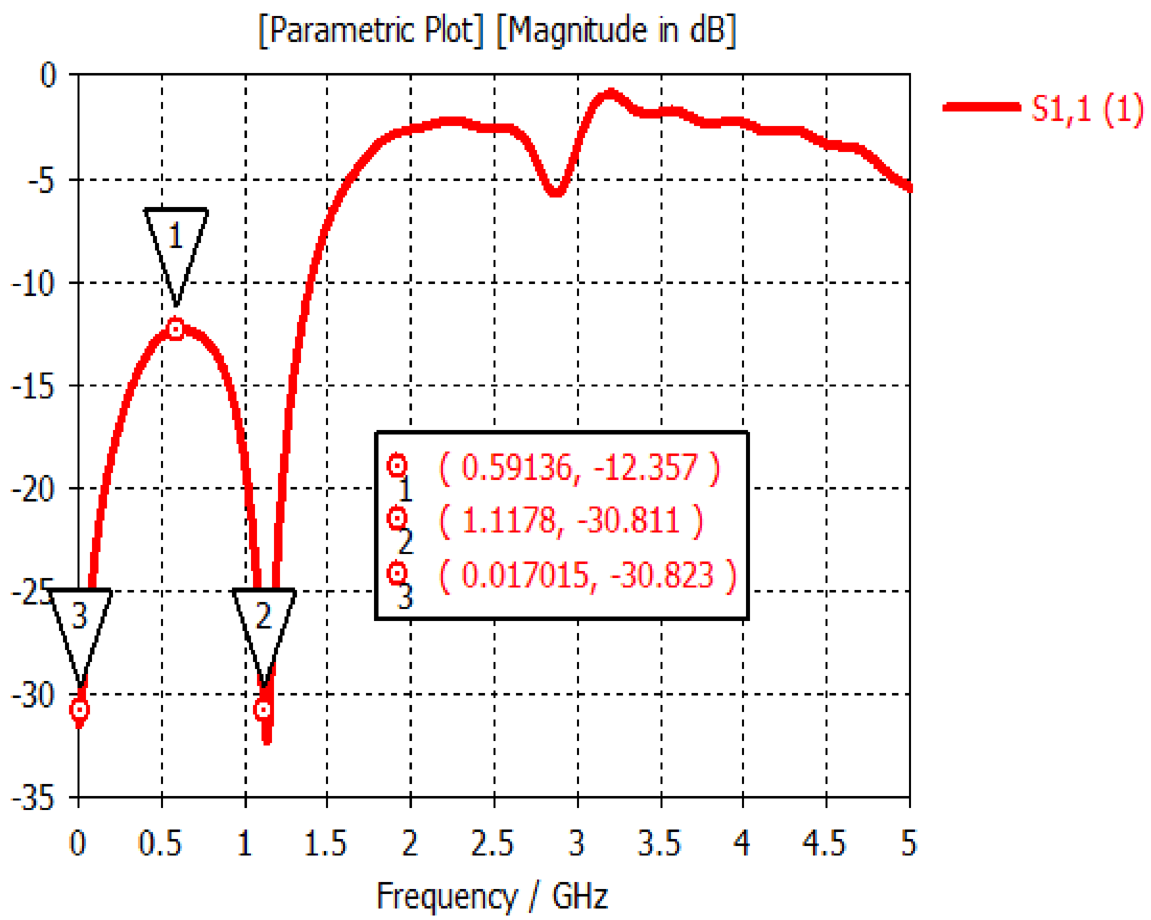


Fig.5.5 S_{11} result of the designed filter.

The S_{11} result which is the return loss, which is the loss of power in the signal reflected, measured at the output of the filter. In Fig.5.5 the average return loss is -12.35dB and the maximum return loss is -30dB at frequency 0.01GHz and 1.11GHz. The simulated S-parameter of the designed filter is shown in Fig.5.6.

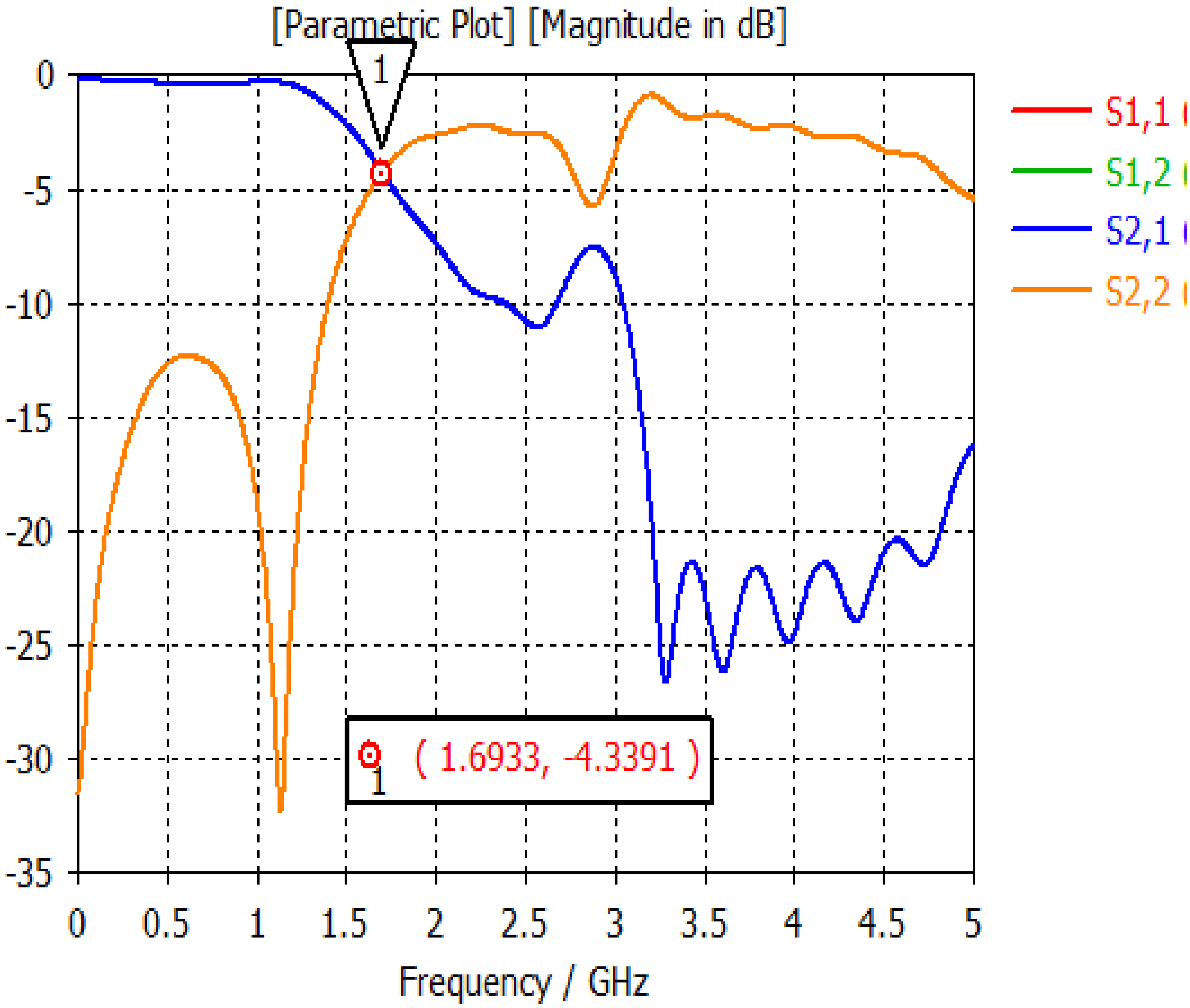
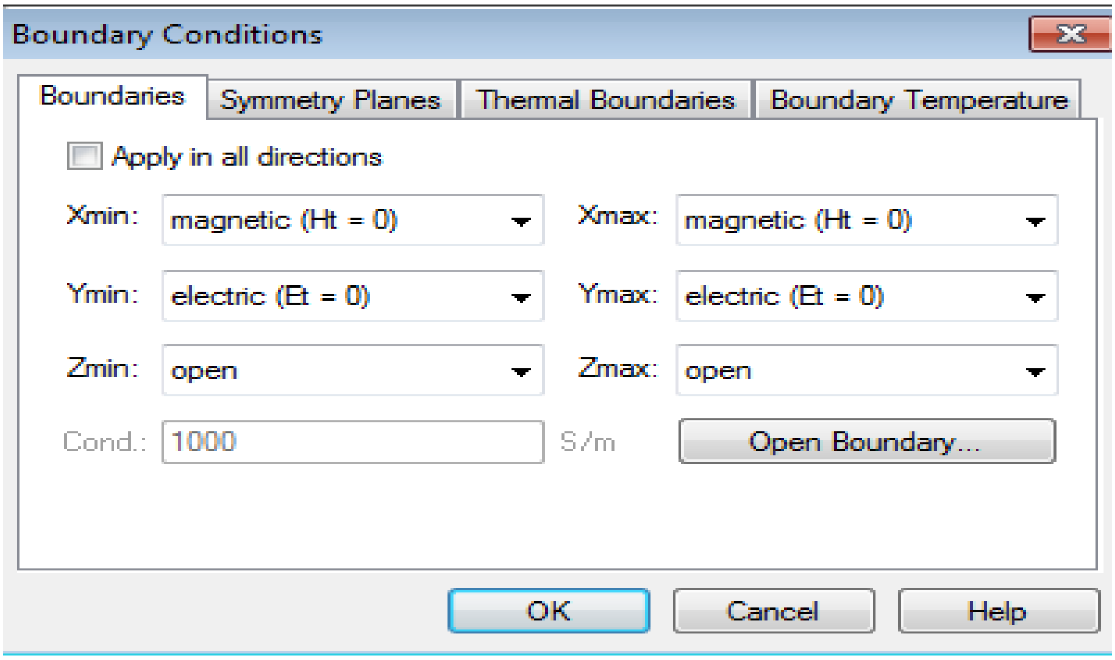
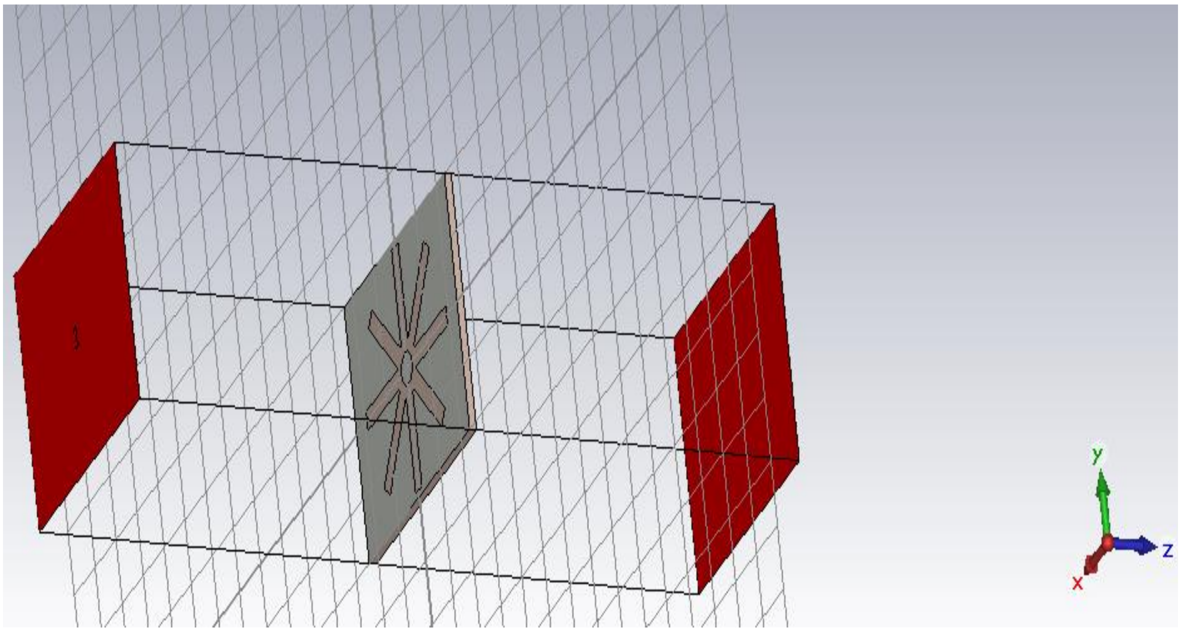


Fig.5.6 simulated result of low-pass filter.

The simulated results of the low-pass filter are shown in Fig.5.6. As one can seen from the results of Fig.5.6 that the pass band region is at an average of -12.35dB, while rejection band for the low pass filter starts at 2 GHz as characterized by S_{21} data. The filter was designed to have a cut-off frequency of f_c=1.69 GHz. The boundary conditions of the designed filter are illustrated in Fig.5.7.



(a)



(b)

Fig.5.7 (a), (b) Boundary conditions of the proposed filter

5.4 Extraction of Effective Material Parameters

Using the CST Microwave Studio Simulator, as the final post processing step after the three dimensional field simulations, effective materials can be extracted. There are different extraction techniques; in this design Nicolson Ross Weir (NRW) strategy has been utilized to calculate the effective material properties from transmission and reflection coefficients. The NRW [67] approach starts by establishing the composite terms

$$V_1 = S_{11} + S_{21} \quad (5.1)$$

$$V_2 = S_{21} - S_{11} \quad (5.2)$$

Then using the above equations, permittivity and permeability are calculated:

$$\mu_r = \frac{2}{jdk_o}\frac{1-V_2}{1+V_2} \quad (5.3)$$

$$\varepsilon_r = \frac{2}{jdk_o}\frac{1-V_1}{1+V_2} \quad (5.4)$$

The simulated results of the permittivity and the permeability of the designed filter are illustrated below:

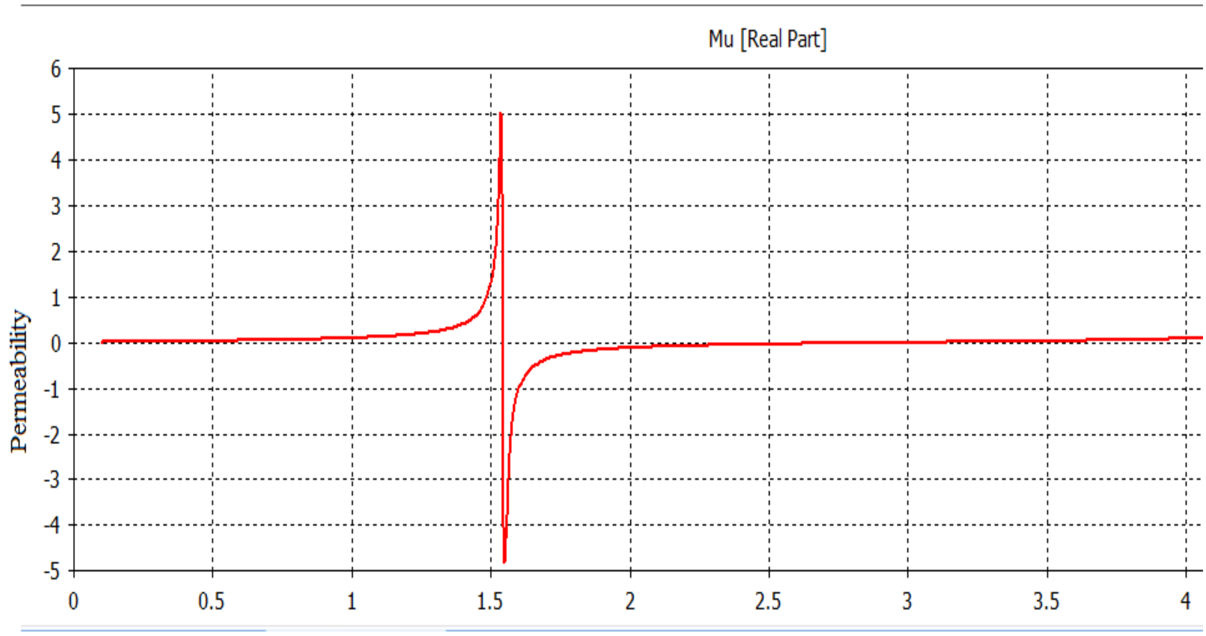


Fig.5.8 Permeability of the designed filter.

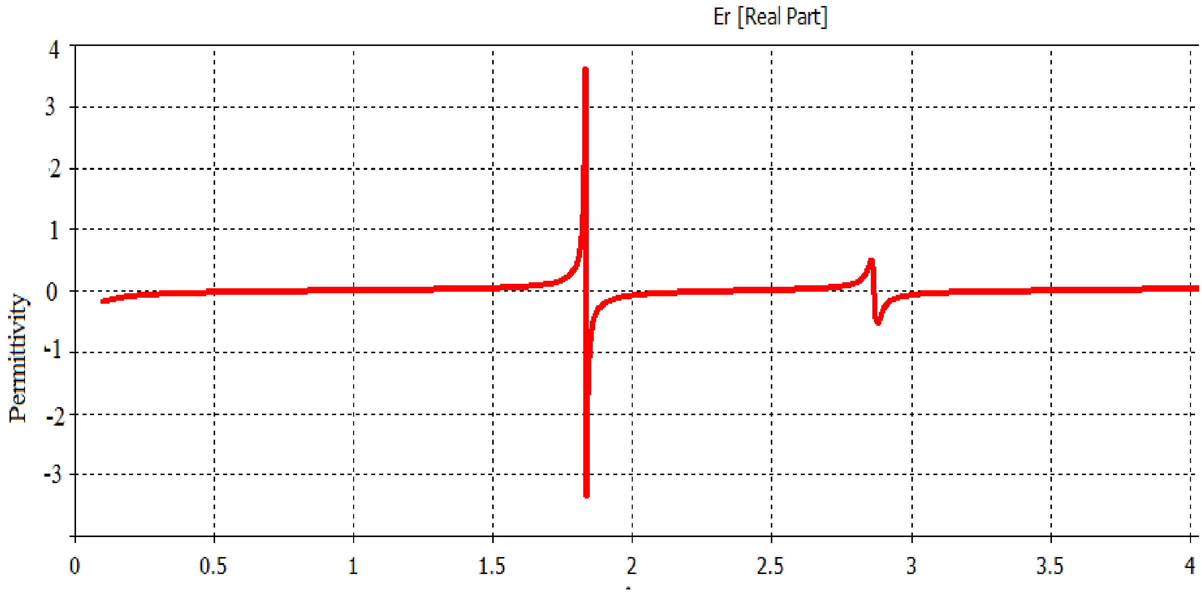
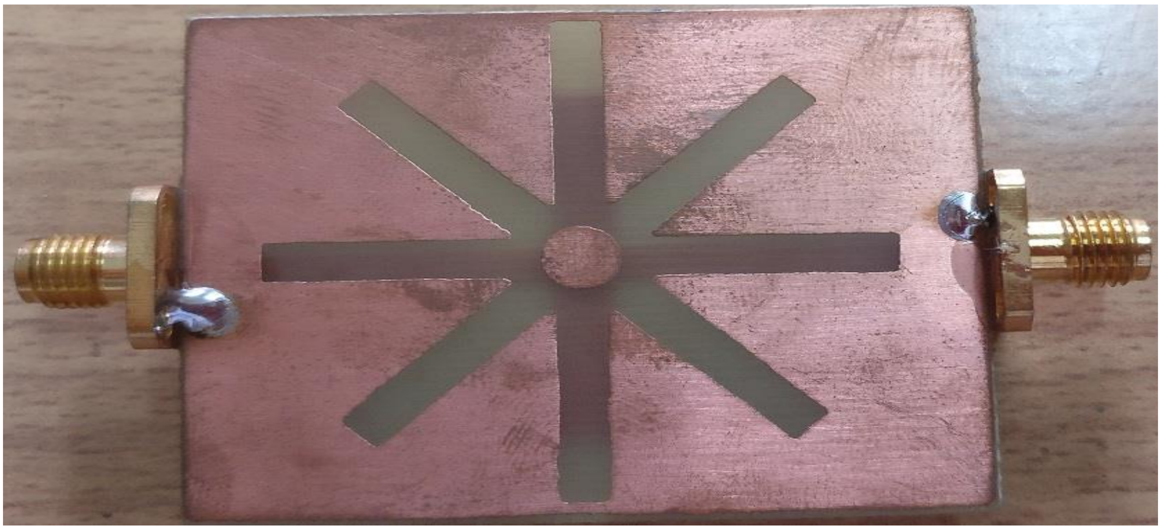


Fig.5.9 Permittivity of the designed filter.

5.5 Fabrication and testing of the designed low pass filter using sun-shaped CSRR

The LPF is designed on a printed circuit board with a copper as the perfect electrical conductor (PEC) on a FR-4 substrate having dielectric constant of 4.30 and a thickness of 1.6 mm. The layout of the transmission line and the sun-shaped CSRR is designed in Schematic and PCB Design Software and then printed on a butter paper for the final fabrication. The patch and the sun-shaped resonator at the ground plane is fabricated using conventional photolithography process. The front and the back view of the fabricated LPF are shown in the Fig.5.10.

(a)



(b)

Fig.5.10 (a) Top view, (b) Back view of fabricated low pass filter.

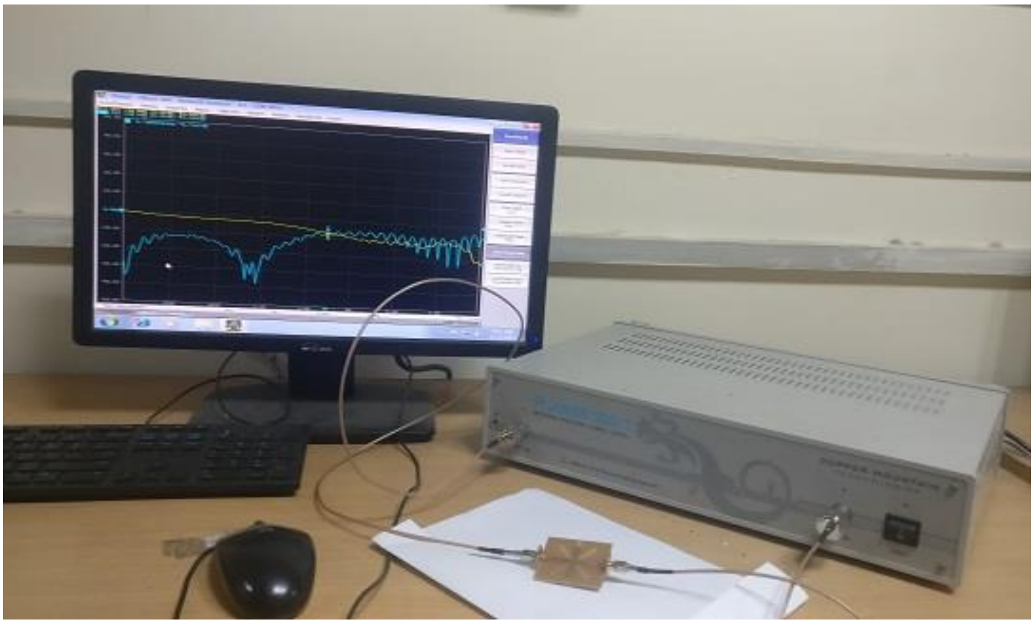


Fig.5.11 Experimental set-up of fabricated filter.

The measurement and testing of the fabricated LPF done using a Vector Network Analyzer (VNA). The tested result of the low pass filter are shown in the Fig.5.12 below:

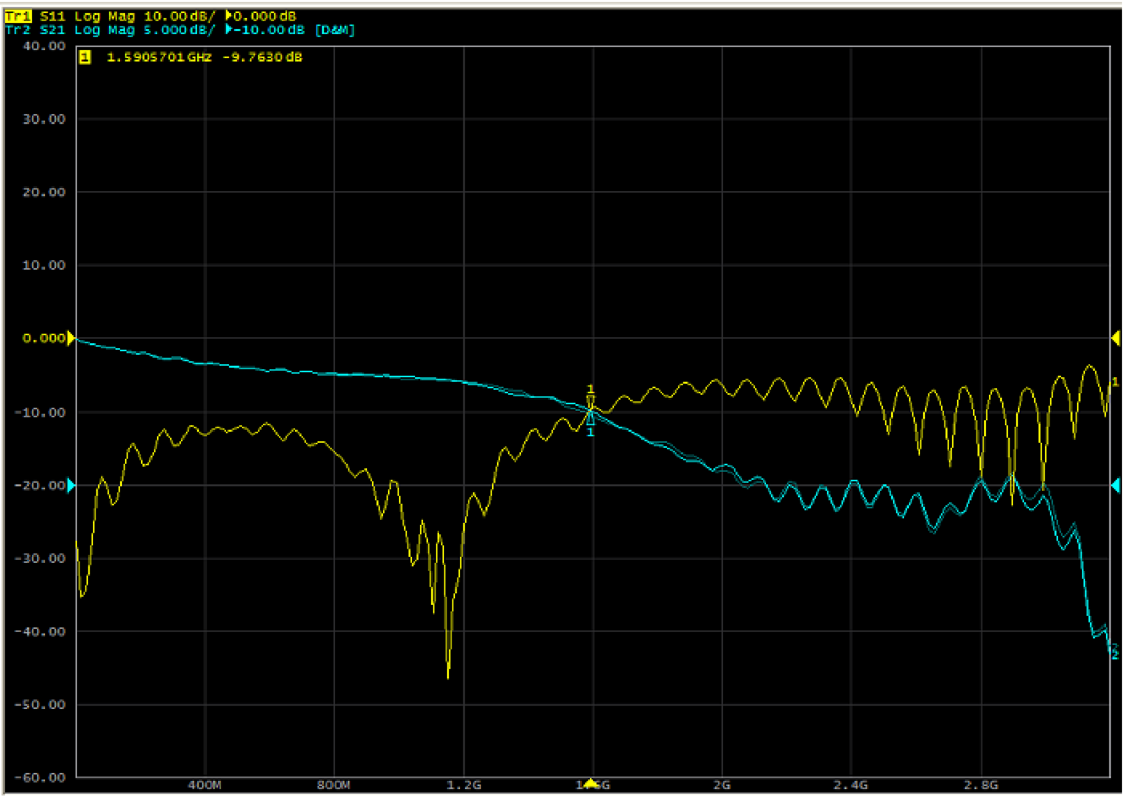


Fig.5.12 Tested result of the design filter.

The tested results of the fabricated filter using Vector Network Analyzer (VNA) are little different than simulated results. The tested results of the low pass filter shows that the cut off frequency of the fabricated component is equal to 1.59 GHz. The simulated filter has cut off frequency equal to 1.69 GHz. The result obtained by testing the fabricated filter is in accordance with the proposed design with some error which is encountered during the fabrication of the components.

CHAPTER-6

Conclusion and Future Scope

6.1 Conclusion

In this thesis work, basic theory of the left-handed material is studied, i.e. how these left-handed materials are different from the existing material and follow the backward propagation of the waves in the material. The advancement and growth in the metamaterials were contemplated and the property of the metamaterials to demonstrate a negative refractive index was additionally analyzed. The thesis analyzed the fundamental idea of metamaterials and how the combination of the wire array and the split ring resonators go about as an essential cell structure for the usage of the metamaterials. The design geometry of the wire and the split ring resonator were additionally examined. The wired array geometry put at the specific separation separated limits the electric field in it and demonstrated a negative permittivity to a specific range called the plasma frequency and the SRR which limits the magnetic field around it creates a negative permeability in a specific range of frequency.

With the basic knowledge of metamaterials where used to design a LPF using sun-shaped CSRR. In microwave systems, LPF is regularly used to get rid of the undesired frequency. Step impedance low-pass filter and open stub low pass filter are generally utilized for this reason. Yet these low pass filter have steady cut-off response. By expanding the number of areas, the rejection characteristics can be better. However, by expanding the number of sections, the pass-band insertion loss increases and also the physical size of the overall filter increase. A few strategies have been accounted to tackle this issue. So a new artificial material is used which is known as metamaterials, using the properties of these unique properties a compact size filter can be designed. The designed LPF using sun-shaped r CSRR with eight slot of equal size at equal distance from each other has been designed. This designed filter has low insertion loss and sharp cut of frequency at 1.69 GHz. The low pass filter was designed on a FR-4 (lossy) substrate with a height of 1.6mm and the relative permittivity of 4.30. The filter designed has eight slots of equal size giving a sun shape which are etched on the ground plane of the substrate. The designed filter has low pass band insertion loss and a sharp cut off frequency at 1.69 GHz. Thus a sun shaped low pass filter with compact size is designed and simulated in CST Microwave Studio. The low pass filter is fabricated and tested to verify the results attain from the simulation.

6.2 Future Work

The future work of this thesis comprises the designing this project using the basic concepts of this unique material known as Metamaterials. These materials can exhibit the negative permittivity and permeability and thus achieving negative refractive index for a composite medium. These metamterial structures which show left-handed properties in microwave band region can be utilized in designing the microwave components like filters, couplers, antennas, etc.

This designed filter can be utilized in microwave to reject the undesired frequency in microwave systems. Moreover the designed low pass filter is compact and small in size as compared to the conventional low pass filters designed which makes a component more efficient and helps in future technology for making miniaturized components for wireless communication. Due to size miniaturization of the components, more and more number of filters can be fabricated in a small region to lessen the cost and material utilized for the last fabricated microwave components.

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