POLITECNICO DI TORINO

Master of Science

in Communication and Computer Network Engineering

Master's Degree Thesis

'Numerical Analysis of Tunable Periodic Structure.'

Academic Advisor:

Supervisor: Prof. MATEKOVITS LADISLAU

Candidate

Fiza Nisa

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ABSTRACT

The numerical analysis of tunable one-dimensional periodic structure is presented in this thesis by developing periodic structures in CST. For this purpose, two structures have designed. In base structure the substrate layer FR-4 is used and then for symmetry reason vias are inserted in first structure and these vias are used to connect the microstrip lines to the main structure. While in the second structure the cut-slots are introduce for biasing purpose. Two microstrip lines are used in both the structure. These microstrip lines are placed independently from the main structure to cope with the increase of complexity structures.

Goal of this thesis is to observe the behaviour of Propagation of waves inside the structure. For this purpose, ten modes are used with two different boundary conditions in both structures and comprised four set of simulation two for each periodic structure. Then the modes that are propagating inside dielectric are selected. The results of the simulations are presented in the form of Dispersion Diagram (DD) which shows the behaviour of wave propagation in terms of frequency vs phaseX (from 5 to 175). The common modes from both the structures that are passing through the dielectric under different boundary conditions are selected. The respective result of the structures is presented in the form of Dispersion Diagram.

The simulation of dispersion diagram is obtained by using a software which is called CST. This software is very friendly, convenient, popular and gives accurate designing results as compared to other software, Chapter 3 contains the detail information about designing process in CST. In the following chapter results and simulation design process are discussed. In the beginning of this chapter the design of first structure is presented then the designed and simulation of second structure have analysed and the result is presented in the form of Dispersion. These structures can be used in further research and experimentation for observing the behaviour of the waves For example the PIN diodes can be placed in these cut slots to get different results and to see different behaviour of waves.

ACKNOWLEDGMENT

I would like to say special Thanks to Professor Ladislau Matekovits for his phenomenal supervision. I have learnt a lot and I got a great experience and skilful knowledge under his extraordinary supervision, that's why special credit to my supervisor whose supportiveness, technicalities, observations were remarkable throughout this journey, His consistent encouragement gave me hope and vision. Furthermore, I would like to say special Thanks to friends and family specially my Parents for their Love, strong support, prayers, and encouragement. They are and will remain close to my heart, I specially say Thanks to Politecnico di Torino, to make me a part of one of the best institutes in the world. To provide me opportunity to learn a lot and to make friends around the world.

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Acronyms

DD	Dispersion Diagram
RF	Radio Frequency
EM	Electromagnetic
CST	Computer Simulation Technology
FSS	Frequency Selective Surface
1D	One Dimensional
2D&3D	Two and Three Dimensional
MM	Metamaterials
TE	Transverse Electric
TM	Transverse Magnetic
TEM	Transverse Electromagnetic
Sub	substrate
EM waves	Electromagnetic waves
HIS	High Impedance Surface
FIT	Finite Integration Technique
Thz	Tera hertz frequency
Ghz	giga hertz frequency
UCM	Unit cell model
MMA	Metamaterial absorber

CHAPTER1

INTRODUCTION

Metamaterial have gained so much importance from researchers around the globe since many years. In field of Electromagnetic these materials have earned significant importance which suggest the use of periodic structure for understanding of high impedance surfaces.

Periodic structures are composed of unit cells that are identical in nature. There are many examples of periodic structure in electromagnetics i.e., waveguides, Frequency selective surfaces, bandgap materials, Metamaterials.

In recent years the periodicity is introduce by using their adoptive characteristics as compared to the main structure. There are several ways by which the periodic structures can be reconfigure up to certain level i.e., by considering tunable materials for example liquid crystal, graphene, or ferroelectrics.

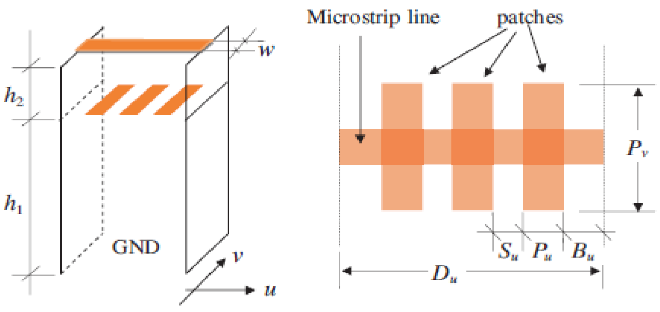


Figure 1: Unit cell with microstrip line [1]

A lot of research has already been done in tunable periodic structure by using microstrip, varactors, diodes etc in this thesis the two microstrip line are used along with the cut slots and vias to make the structure tunable and to analyse the behaviour of waves Propagating in the dielectric. Surface waves are observed by analysing one dimensional dispersion diagram

In chapter 2 of this thesis a Brief Literature review about the periodic structures, metamaterials, Dispersion Diagram is presented and in chapter 3 the designing tool CST which is used in the designing of both the structure its methodology is described step by step.

The next chapter contains the design details and results discussion of both the periodic structures, their wave propagation behaviour dispersion diagram.

In final Chapter the conclusion of the thesis is present.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Initial Information about periodic structure

In nature periodic structure are present in different forms and these structures consist of unit cell that are like repeating a building block. Band gaps are present in periodic structures.

Periodic structure is made up by assembling same elements known as unit cells in one or two dimensions. There are two ways to excite a periodic array the one is active array type in which each element has attached generators and the other way is the passive array type (By incident plane) In Passive array type the plane wave which is coming E_i in the forward direction it will be transmitted partially E_t and reflect in specular way as E_r. The Coefficient (Γ) of specular reflection is define as [7]

$$\Gamma = {E_r}/{E_i}$$

In many areas of science and engineering the Periodic structures are frequently used. The propagation of electromagnetic waves all over the structure can be tailored by changing the unit cell's geo-metrical parameters [8].

Waves are not able to propagate in these bandgaps as these are the frequency intervals. Modes are used to represent the Waves propagation in enormously extend structures. [1]

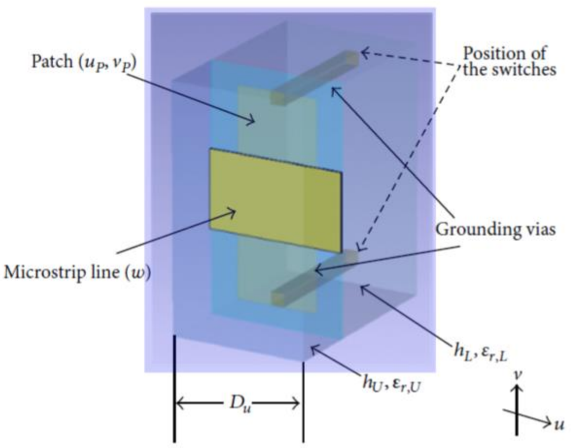


Figure 2.1 :Single unit cell of periodic structure with microstrips lines [2]

Here the periodic structure's numerical analysis has been presented. The design consists of microstrip line and patches, its grounded two-layer configuration in which two vias are used to connect the ground plane to the patches present below the microstrip line. the on the top of structure microstrip line is loaded orthogonally by sequence of patches.

In this thesis the propagation of electromagnetic waves is depicted in the form of frequency vs phaseX over 18 points in 10 modes and are presented in the result section.

2.2 Microstrip line:

In recent communication networks, created on microstrip technology the planar antennas are broadly used as their fabrication is easily possible at less cost. These are highly desirable due to their adoptability in modern application yet for certain applications the technical requirements are difficult to deal such as the applications that needs higher polarized purity, much broader bandwidth, or the phase of reflected wave's control requirement.

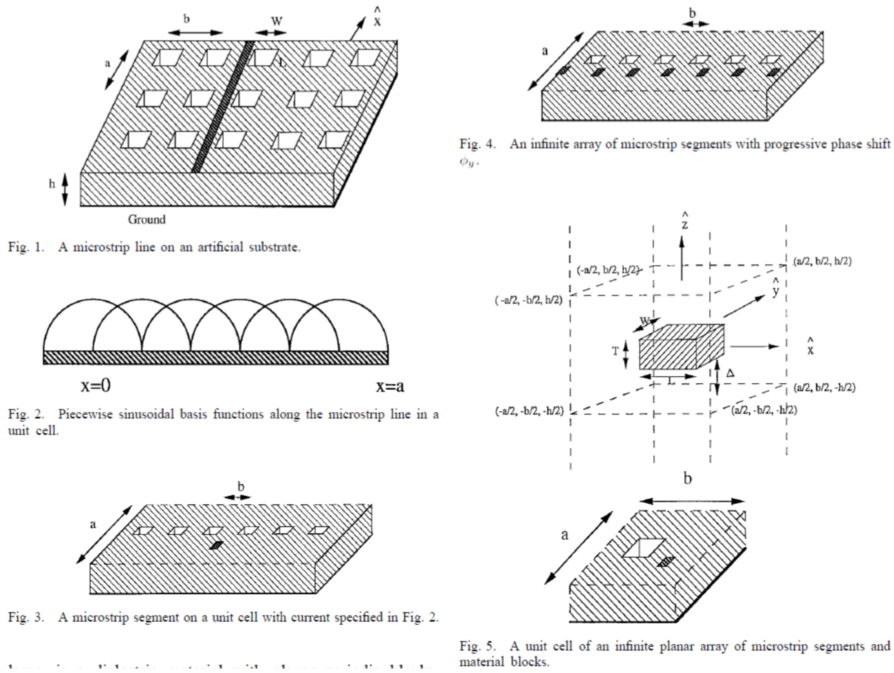


Figure2.2: Geometry of a microstrip line on an artificial periodic substrate [3]

In the Figure above we can see in artificial periodic substrate the geometry of a microstrip line. With planar periodic blocks the substrate is a dielectric material. It is shown that in these types of structures the propagation of surface waves can be eliminated partially [3].

2.3 Basics about Metamaterials

The word MM is basically known as these periodic structures, as they are not naturally present, and the configurations are realized artificially [2]. Victor Veselago a Russian physicist discussed and proposed the metamaterial theoretically for the first time in 1968 [9]

Victor Veselago examined the negative values of permeability and permittivity of the substance at the same time. And he investigated that in such material how the electromagnetic waves travel and aboust their characteristics. Although till 1996 it was not possible to get negative values of permittivity and permeability through experiment, till john B.Pendry et al found it in 1996 [10].

He suggested that with the specific radius and particular gap of a periodic array of copper wire can generate an electromagnetic response of permittivity materials. Furthermore, he stated that band gap frequency could have in split ring resonator's periodic array due to the negative values of permeability.

Because of wonderful properties the MM are the great discovery of this time. Current development in. By tuning its properties one can get desired characteristics. Current innovations in the field of technology are developed in the way in which every passing day the life becoming smarter and smarter from transport to high rising building, home to industry, all the things are going quick its all possible because of unique discovery of MM. These are artificial materials that are utilized to get the required characteristics by tailoring to an application whereby natural way it is not possible. It is a Greek word which mean 'beyond' MM are comprised of UCM that are made up by arrangement of sub wavelength that are made by periodically repeating pattern.

Metamaterials are composed of variable material i.e. glass, fibre, polymer, metal etc. There are different properties related to it such as positive refractive indices, optical frequency, impedance matching zero reflection, magnetism, absorption, negative refractive indices, and nonlinear properties. More beneficial uses of MM include cloaking device, advance antennas, radar and ultra-high resolution imaging systems.

The dipole moments are thoroughly linked to the permeability and permittivity of the composite medium, these electric and magnetic dipole instants are induced as soon as electromagnetic waves strike a composite medium. material with precise electromagnetic response can be produced as the designer of the material can control the shape, size, density, and direction of inclusion. These artificially designed materials are called metamaterials [9].

2.4 Tunable Metamaterial

Frequency can be changed according to requirement in tunable metamaterial. Different results can be seen when the EM wave interact with the material in tunable MM. The tunable MM has an ability that is to be reflected, transmitted, and absorbed the EM wave. In tunable metamaterial the lattice configuration in real time is dynamic which permit the reconfiguration of the MM system during operation.

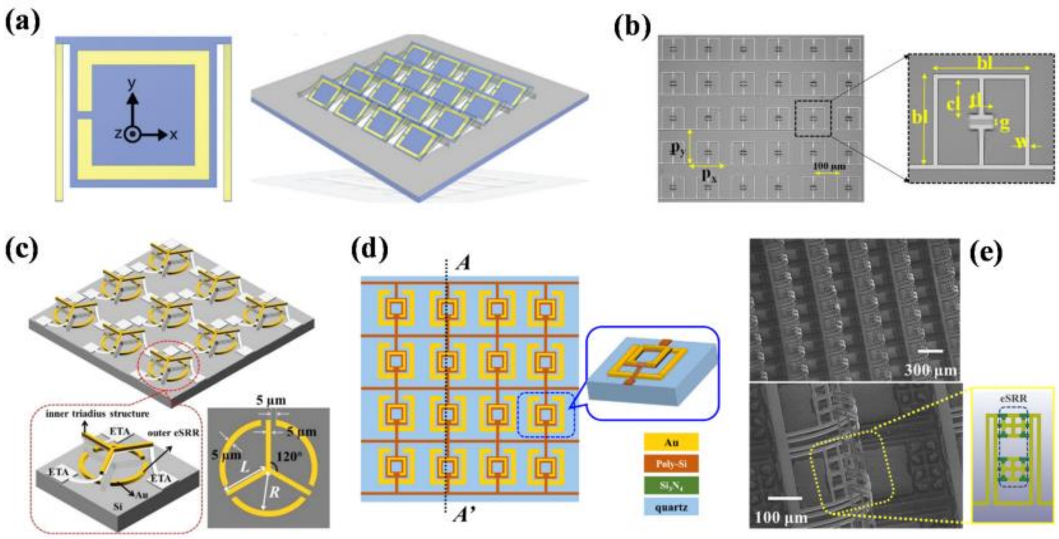


Figure2.3: Different Types of Tunable Metamaterials [4]

2.5 Metasurfaces:

Meta surfaces are two dimensional through their electric and magnetic polarizability it is possible to characterise their response which is same as metamaterials.

Because of tailored value of permeability and permittivity Metamaterial regulate the propagation of light yet propagation effect still uses by metamaterial to operate magnetic waves which results in complex bulky structure. In comparison metasurfaces attempt to operate the wave on thin layer [9] [10].

Metamaterials are 3D in nature so as hard to fabricate whereas the metasurfaces are two dimensional due to which they are less lossy in structure and less bulky. Using planar fabrication tool, they can be easily fabricated because of their planar structure.

2.6 Frequency Selective Service

Frequency Selective structure is periodic structure when every element at resonant frequency have resonance. In signal communication to Provide spectral filtering FSS are commonly used [9].

These are the spatial filters in which the electromagnetic waves can be transmit, absorb, or reflect. These are used as band pass, low pass. There are some filters that are used commonly are radoms, RCS (radar cross connects) etc in different applications. These filters are broadly use in radar applications and communication. The main goal of FSS is built on the electromagnetic wave's transmission and reflection in particular frequency band.

In FSS the structure which are consist of diodes there is need to add other elements like microstrip lines because diodes cannot be directly biased.

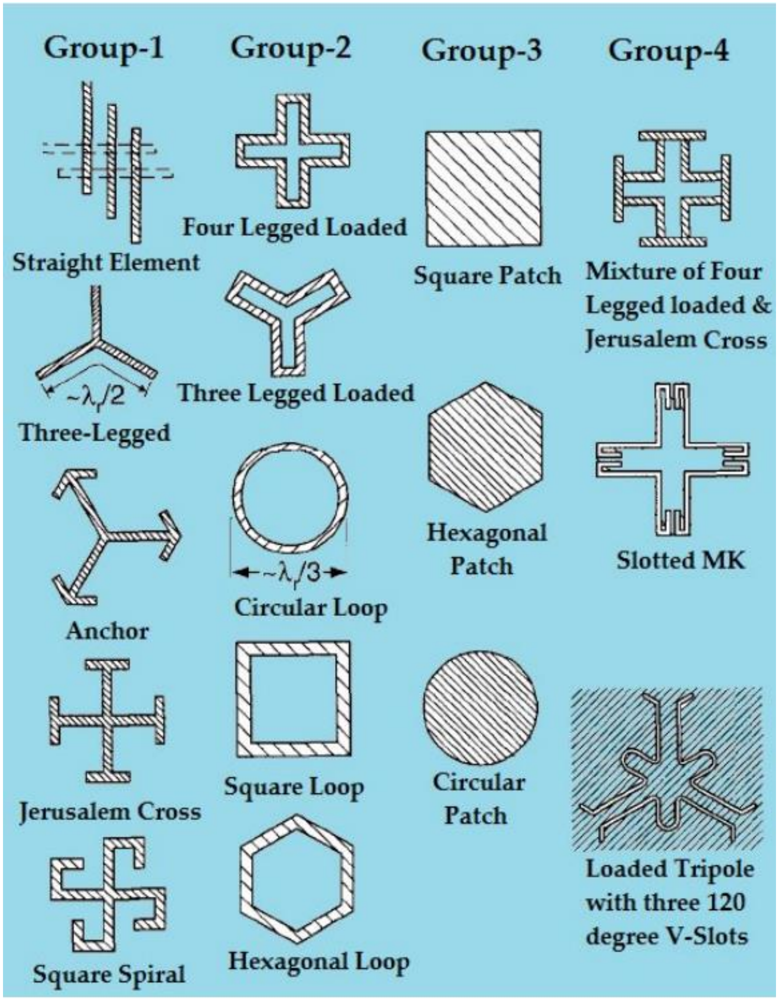


Figure 2.4 Different types of FSS structure [7]

2.7 Dispersion Diagram

DD represents the difference between frequency vs wave number and is used to describe the electromagnetic wave propagation in periodic structure [1].

Dispersion Diagram is used to examine the left-handed abilities of periodic structure and metamaterial. To plot waves of variable frequencies passing at different phase and group velocities this Dispersion diagram is used as it has capacity to study any unit cell of a periodic structure because periodic structure is composed of identical unit cells.

DD provides valuable information on attenuation, phase velocity, radiation losses, coupling between high order [8].

Occasionally, it is called a k-β diagram, in which β is wave propagation or phase constant, and k is wave number since the dispersion diagram is developed from the dispersion equation [6].

To Plot k-β layout in 2D and 3D is difficult, but it is quite easier and simpler for a 1D periodic structure. So, for the complex diagram for advanced dimension another exceptional solution is available which is called the Brillouin zone, which is after the name of Leon Brillouin.

Besides following the constant and Propagation directions the Brillouin allows to validate zones to group propagating directions.

All likely directions of propagation in Y and X axes are able to be combined in an irreducible Brillouin zone which is essentially Triangular area and only limitation on this zone is that it is effective when some symmetry axes exist.

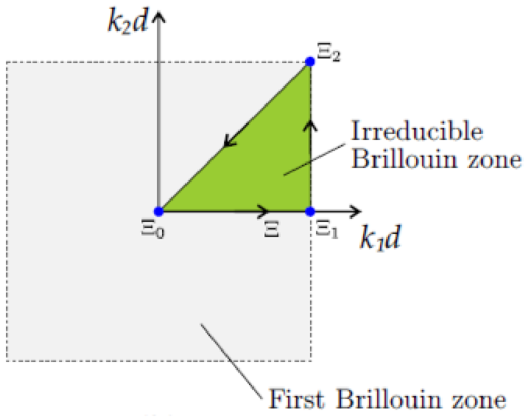


Figure 2.5: First Brillouin zone and the irreducible Brillouin zone [5].

We can see the selection of triangular area for this zone which is optimising the square patch in figure2.5 Moreover, Along the direction of x and y the βx and βy which are the values of phase constant can be seen.

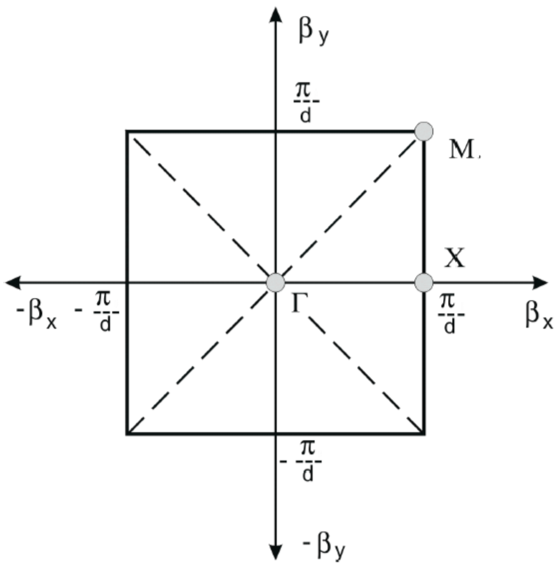


Figure 2.6: Brillouin zone of any geometry with symmetries [6]

The unit cell's geometrical dimension is denoted by d in above picture. There are three possible steps by which the analyses of 2D square patch by dispersion diagram when frequency dispersion of the wave phase variation Γ to X, X to M, and M to Γ.

Γ to X: Along the x-axis it states the phase constant, or it is the base of the

Brillouin triangle. It varies from 0 to 180 degrees whereas y-direction is fixed at 0 degrees. It will be capable to generate the wave propagation's dataset as soon as the phase constant values are set.

X to M: y-direction differs from 0 to 180 degrees, while setting the x-direction 180 degrees fixed. By this method, the next set of eigenmode frequencies are shaped.

M-Γ: final set of frequencies are created for this segment, i.e., M-Γ of

the Brillouin triangle as both the segments are diverse that are Γ-X and X-M from 180

to 0 degrees

To obtain the results in 1D dispersion diagram we use the CST Microwave studio the details are included in next chapter. The dispersion diagram is a graphical depiction of eigenmode frequency as a function of the phase constant [6].

CHAPTER 3:

Design Methodology

3.1.1 Introduction of CST Microwave Studio

CST Studio Suit is used in designing the structure i.e., Structure with via holes and structure with Cut-slots for the study of numerical analysis of tunable periodic structure. The respective results of both the structures are shown in the form of Dispersion Diagram.

CST Studio Suit is selected due to the fact CST is primarily based totally on Finite Integration in Technique and it is extra famous amongst antenna designers and additionally this sort of software program is easy to use and its user friendly.

Parallel Plate Waveguide

To Guide propagating waves this device is use which consist of a dielectric between two conducting plates

Main working method of this is that at specific voltage it generates an electric field which are vertical to the plates, in y direction there is magnetic field and in x direction the electric current flows and in the z direction the electromagnetic waves propagate.

Three modes of a waveguide.

1: TM Mode: In this kind of mode the electric filed is not transverse, but the magnetic field is totally transverse ($E_z \neq 0$ whereas $H_z=0$)

2: TEM Mode: In this kind of mode both fields electric and magnetic are directed component ($H_z=0$, $E_z=0$)

3. TE Mode: here the magnetic field is not purely transverse to the propagation direction but, the electric field is transverse completely ($H_z \neq 0$ whereas $E_z=0$)

3.2.2 Detail of Defining Parameter

It is extremely suggested to rigorously check the setup of software system before going to the design Procedure.

In figure3.1 First we select Microwaves& RF/OPTICAL then Periodic Structures the most important phase for designing Tunable periodic structure because it provides exact setting for making full-wave analysis Then as illustrated in the Figure3.2 we select the FSS, Metamaterial- Unit.

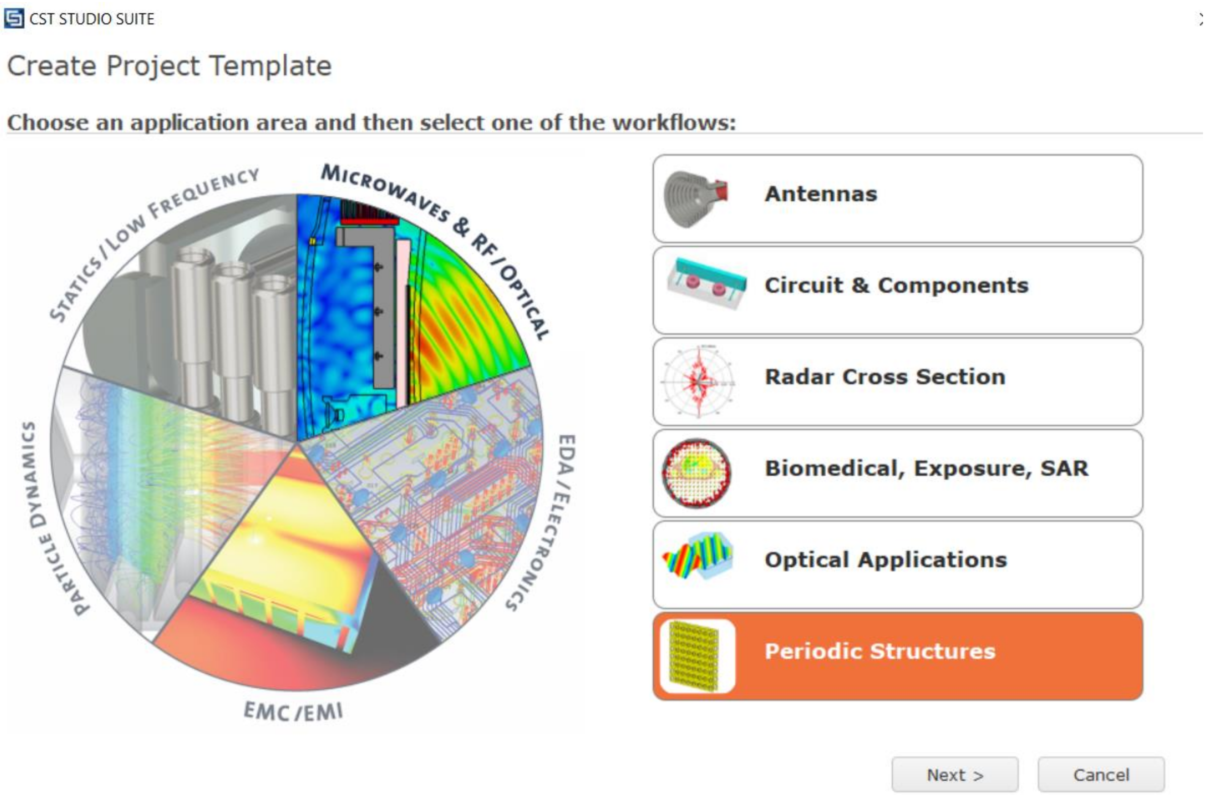


Figure 3.1: CST selection of periodic structure

Furthermore, we select the Dispersion Diagram option through which we analyse results by running the simulation in Eigenmode Solver as shown in the figure 3.4 and fig.3.4, respectively.

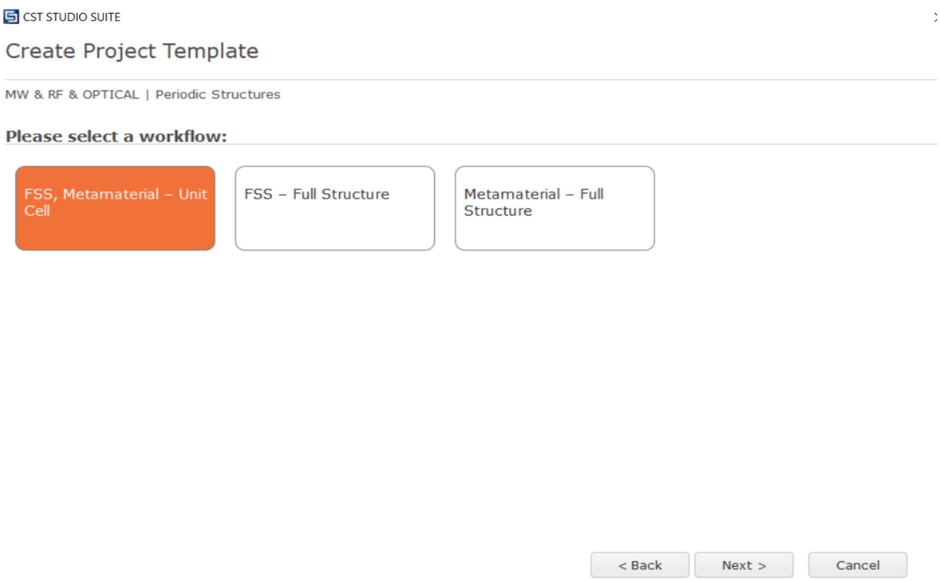


Figure 3.2: CST selection of FSS, Metamaterial-Unit Cell

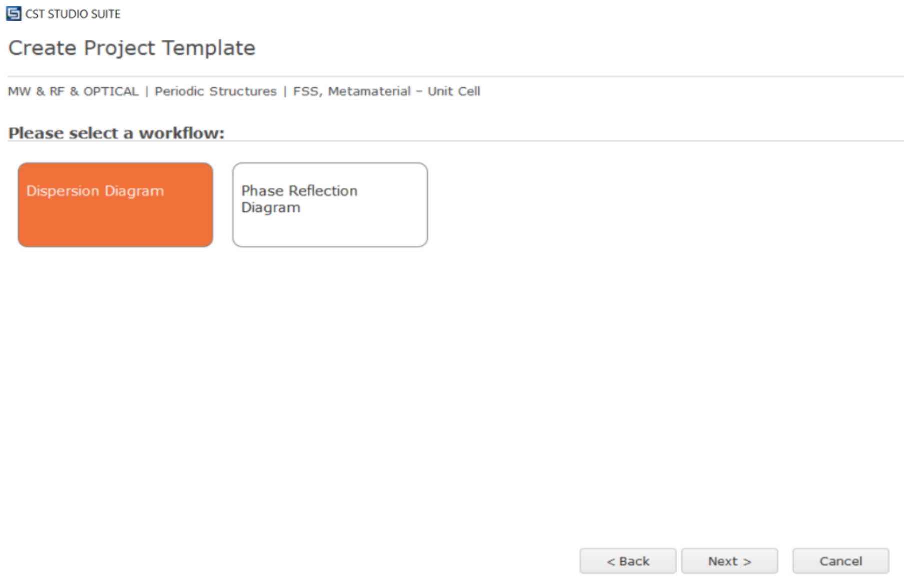


Figure3.3: CST Dispersion Diagram

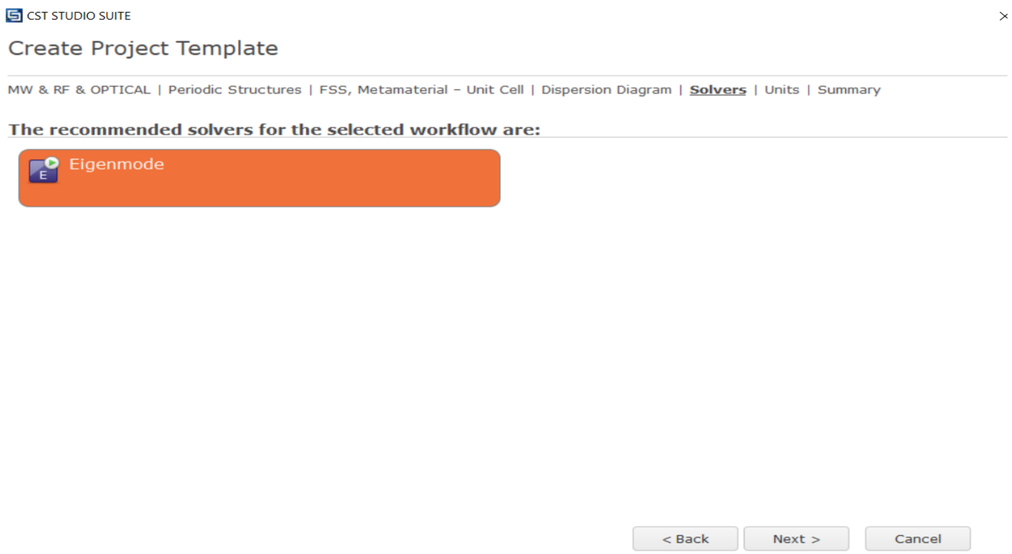


Figure 3.4 CST selection of Eigenmode

The Detail Discussion about the structure is presented in next chapter but it is important to show here that for each simulation we have to setup the background Properties as shown in the figure 3.5 and it is also necessary to define the respective boundary condition as shown in the figure 3.6. In this thesis four simulation are performed that are based on the selection of boundary condition. The boundary condition for z min and z max electric- electric or magnetic -magnetic for both structures, the boundary conditions of x and y are periodic for every simulation.

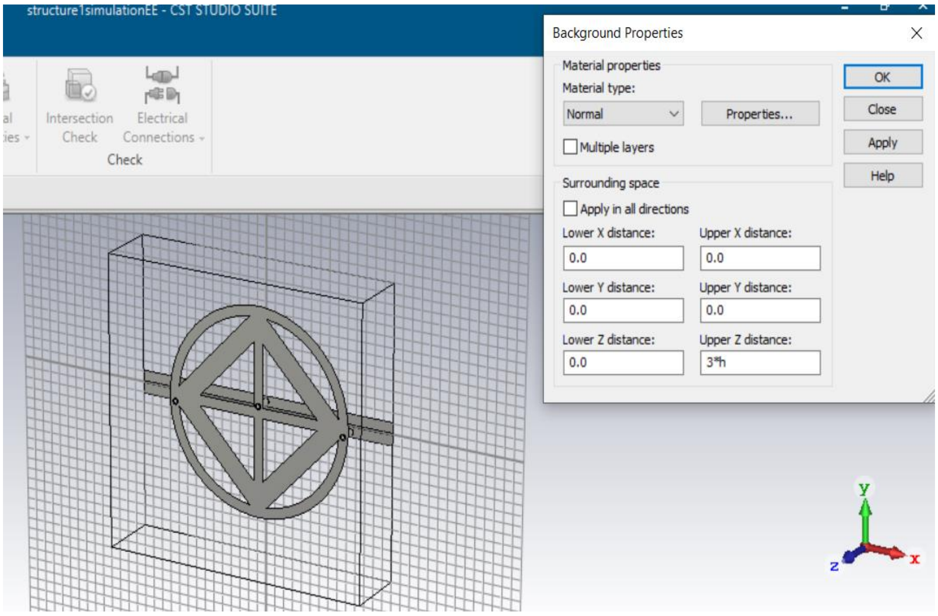


Figure 3.5: CST Background Property

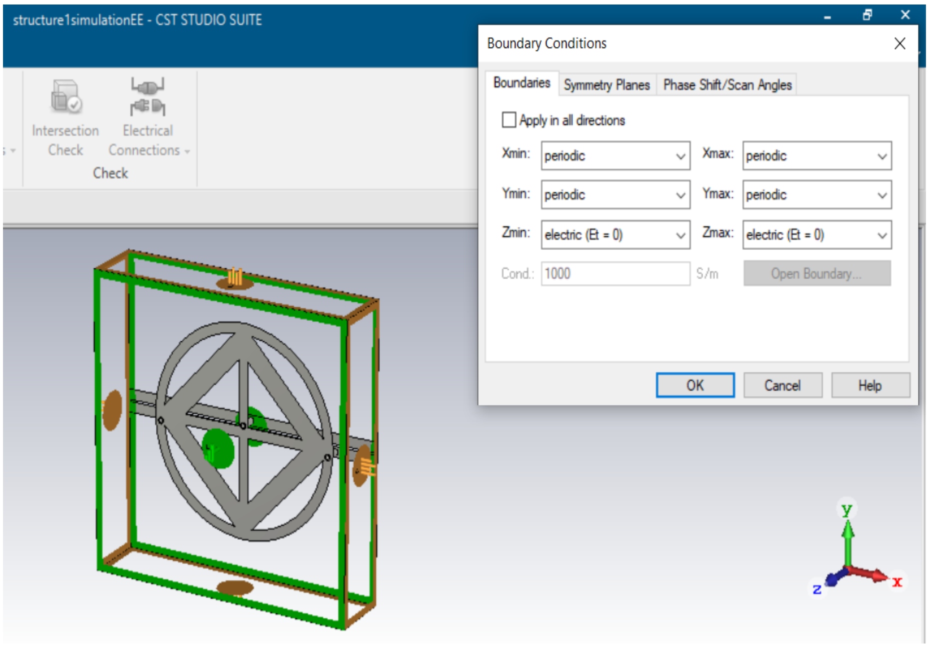


Figure 3.6 CST boundary condition selection

After Designing the structure and putting all the boundary conditions, Frequency selection, background properties. The modes are created in the post template by click on the post processing icon as illustrated in the figure 3.7. In this thesis 10 modes are used by selecting 3D eigenmode results.

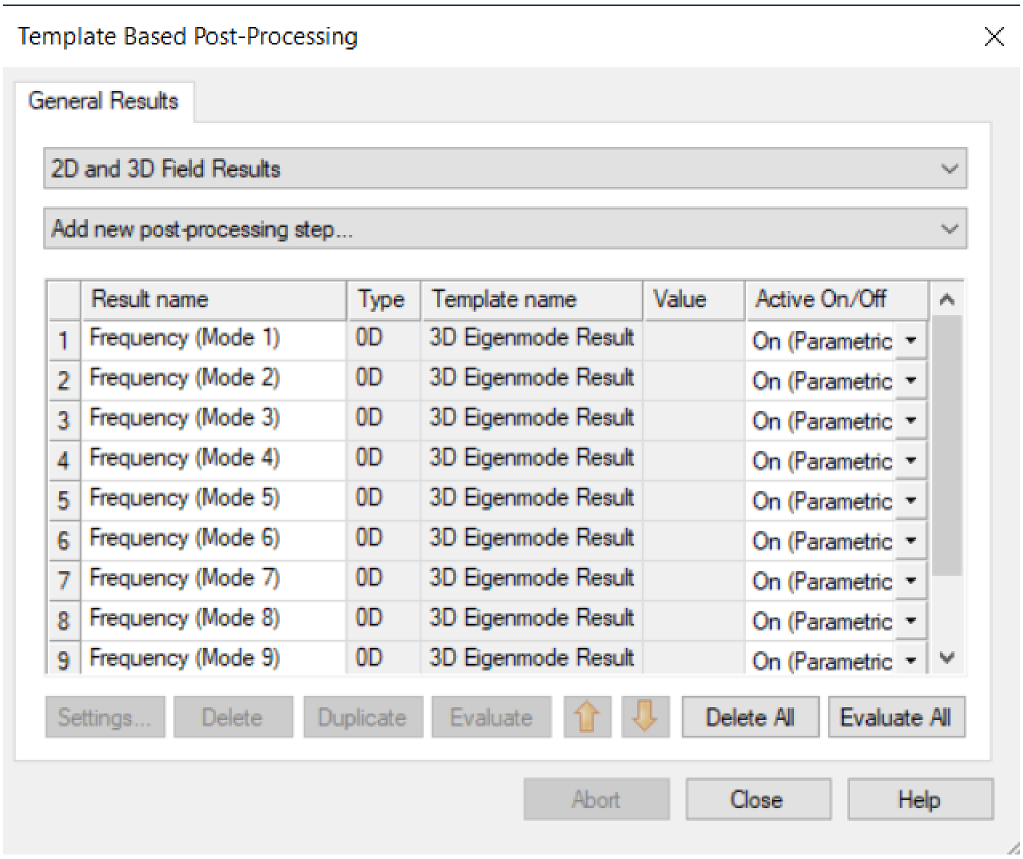


Figure 3.7: Creating modes in CST

For simulation there is need to select a sequence and parameter in parametric sweep. In this thesis phaseX is used in sequence parameter with the values from 5 to 175 over 18 points instead of 0 to 180 degrees to avoid complex computations.

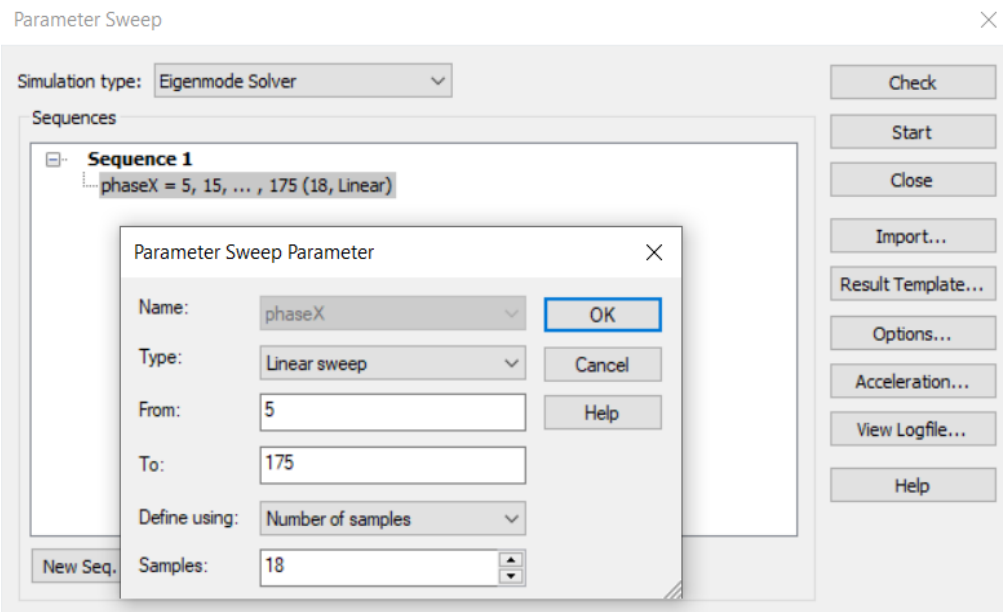


Figure 3.8 Parameter Sweep

CHAPTER 4

Design Of Structures and Results Discussion

4.1 Designing of Tunable Periodic Structure

Every step of periodic structures is presented in this chapter with complete details and illustration. This part is mainly dedicated to the design of Tunable Periodic structure. At the bottom of the structure there are two parallel microstrip lines which are through via holes connected to the frequency selective service. Many researchers around the world used different method to configure the biasing of the structure such as coplanar transmission line insertion. Biasing a network as a high impedance surface with an active part is presented in this journal [11]. The aim of this thesis is to make a tunable periodic structure. For tunning the periodic structure, it is necessary to add some elements [2]

4.1.1 Parameter details for base structure

Selection of dielectric material is the most important thing for acquiring the tunability, Here, in substrate layer the FR-4 is used. In the figures below the important design conditions of the initial symmetric structure is presented. In Figure 4.1 the structure's top view is illustrated. This Structure is formed using FR-4 substrate layer with tan δ= 0.025 and epsilon=4.3,

The Length of the substrate is 14mm and its width is also 14mm the height of the substrate is 1.6mm. The dimension of the circle present in the structure is 10 mm with width 1mm and height is 1.6mm and the square is 7mm with width 2mm.The two lines embedded in the circle is of length 10mm.

Geometry of initial periodic structure

Parameter	**Unit**	**Value**
Dv	Mm	14
Du	Mm	14
Lines inside the circle=L Width of the lines	Mm Mm	10 0.5
Circle	Mm	10
Square	Mm	7
H	Mm	1.6

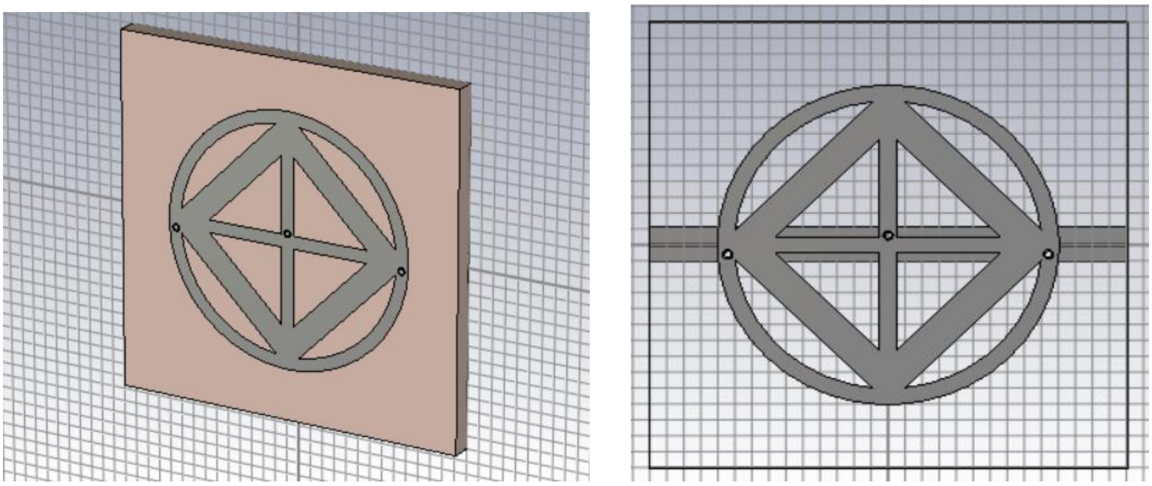


Figure 4.1 Base structure & designing of circle and square.

In the figure 4.2 the placement of three vias and the thickness of the substrate can be seen.

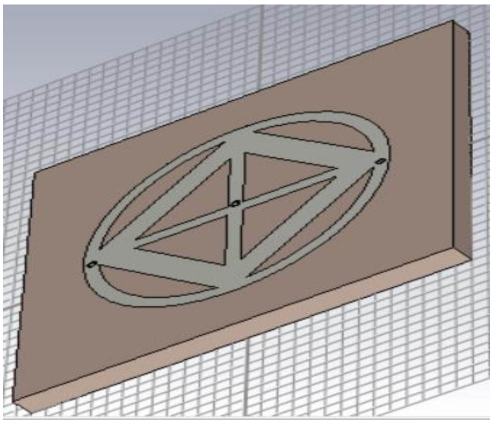


Figure 4.2: Shows thickness of the substrate of structure

4.1.2 MICROSTRIP LINES AND VIA-HOLE

In the substrate two parallel microstrip lines are embedded as shows in the figure 4.3 Both the microstrip lines are equal in length Lm=14mm that corresponds to the periodicity in the x and y direction and width=0.5mm. The key aim microstrip lines are to carry DC for biasing the structure.

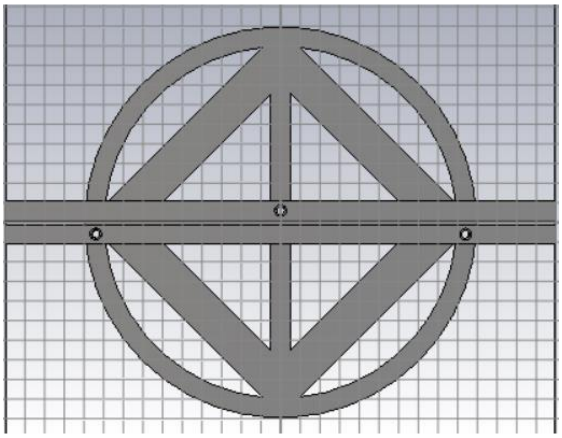


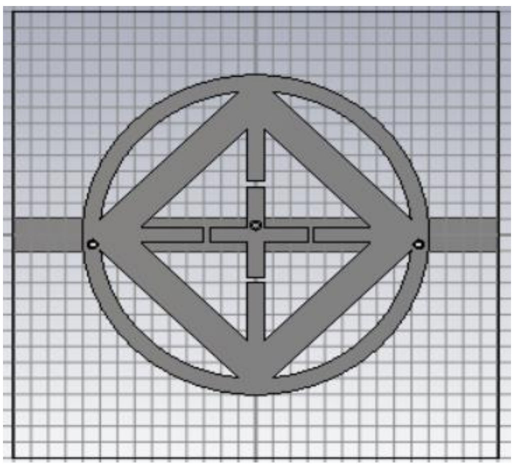
Figure 4.3: Back view of structure

4.1.3 Designing Of structure with Via-holes

The main goal of this thesis is the Numerically analysis of Tunable periodic structure to fulfil this goal the via-hole are used for biasing purpose. for this purpose, the idea of biasing through microstrip lines is introduce but for making the biasing probable through microstrip lines. via-holes are very sensed to join the FSS to the microstrip lines. In this structure three via holes are inserted all with same dimension. The dimension of via-hole described as the outer radius of cylinder shape Rout=0.3mm and the inner radius of cylinder Rin=0.2mm and the position of the via holes are shown in the above figure 4.2 and 4.3

4.1.4 Structure with cut-slots:

In this thesis the cut slots are created just to observe the EM waves propagation in such structure. The cut slots are now commonly use for inserting PIN diodes to analyse the ON and OFF condition of PIN diodes for both TM and TE incidence. But here in this thesis we are only focusing on cut slots and their position.



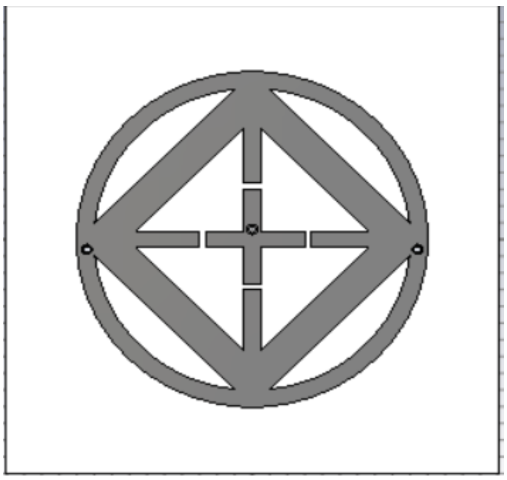


Figure 4.5: Structure with cut-slots front view

Four Cut slots are created in the second structure after attaining a concluding structure in terms of the position of via-holes for making the periodic structure tunable.

The dimension of the cut slots can be made according to the requirements as for example if the diodes are going to be inserted in the cut slots, then the cut will be sized according to the size of diode which will be mentioned in the diode's instruction guide.

In this thesis the dimension of cut slots in this thesis are 1.5mm in width and 0.50mm in length.

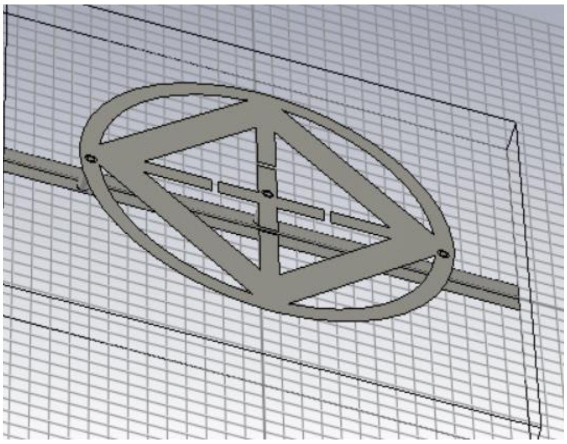


Figure 4.6: Tunable periodic structure with vias, cut slots,and microstrip line.

Before simulation the dialectric air layers are inserted at top and bottom of the structure to avoid the short circuit of the structure.The bottom layer is depicted in the figure: 4.7.

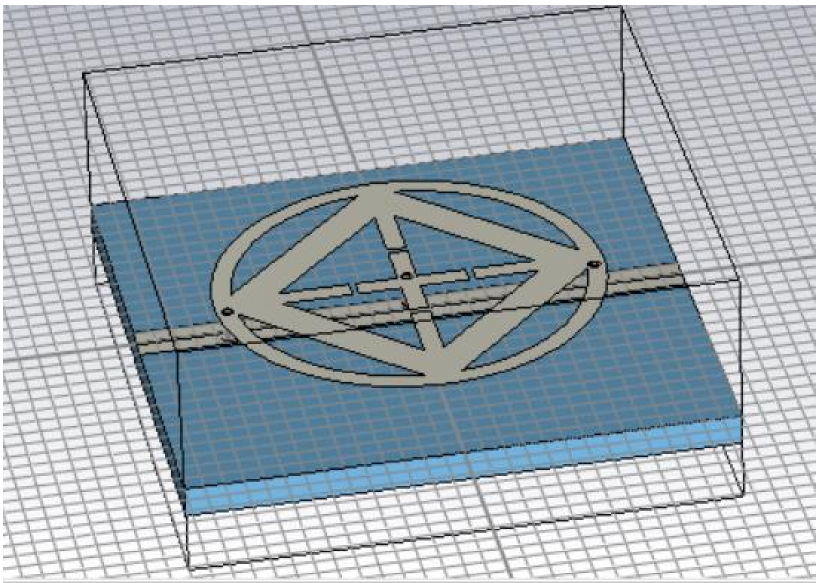


Figure 4.7 structure with dialectric air layer

An additional air layer is been define along with the dialectric layer as shown in the fig

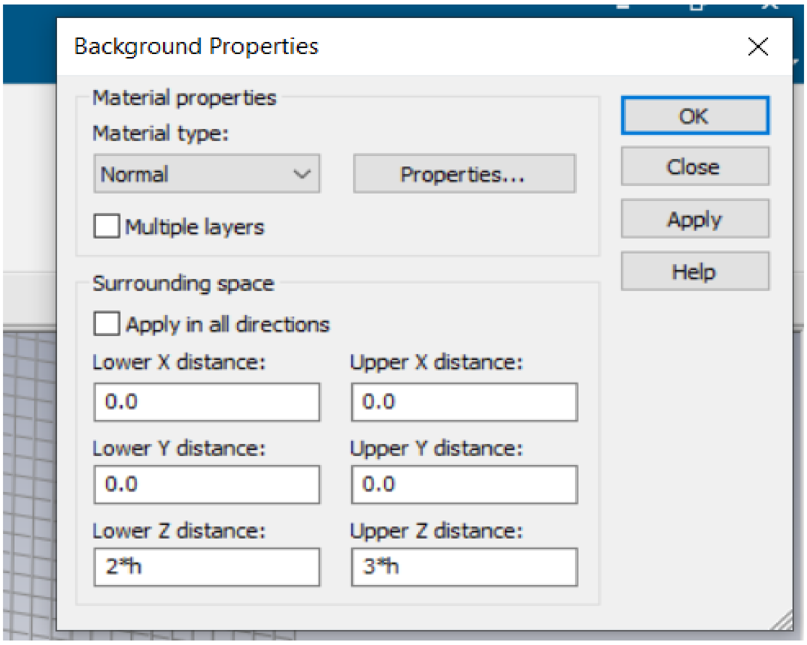


Figure 4.8 Background properties

For simulation of the structure with cut slots the boundary condition is selected as depicted in the following image

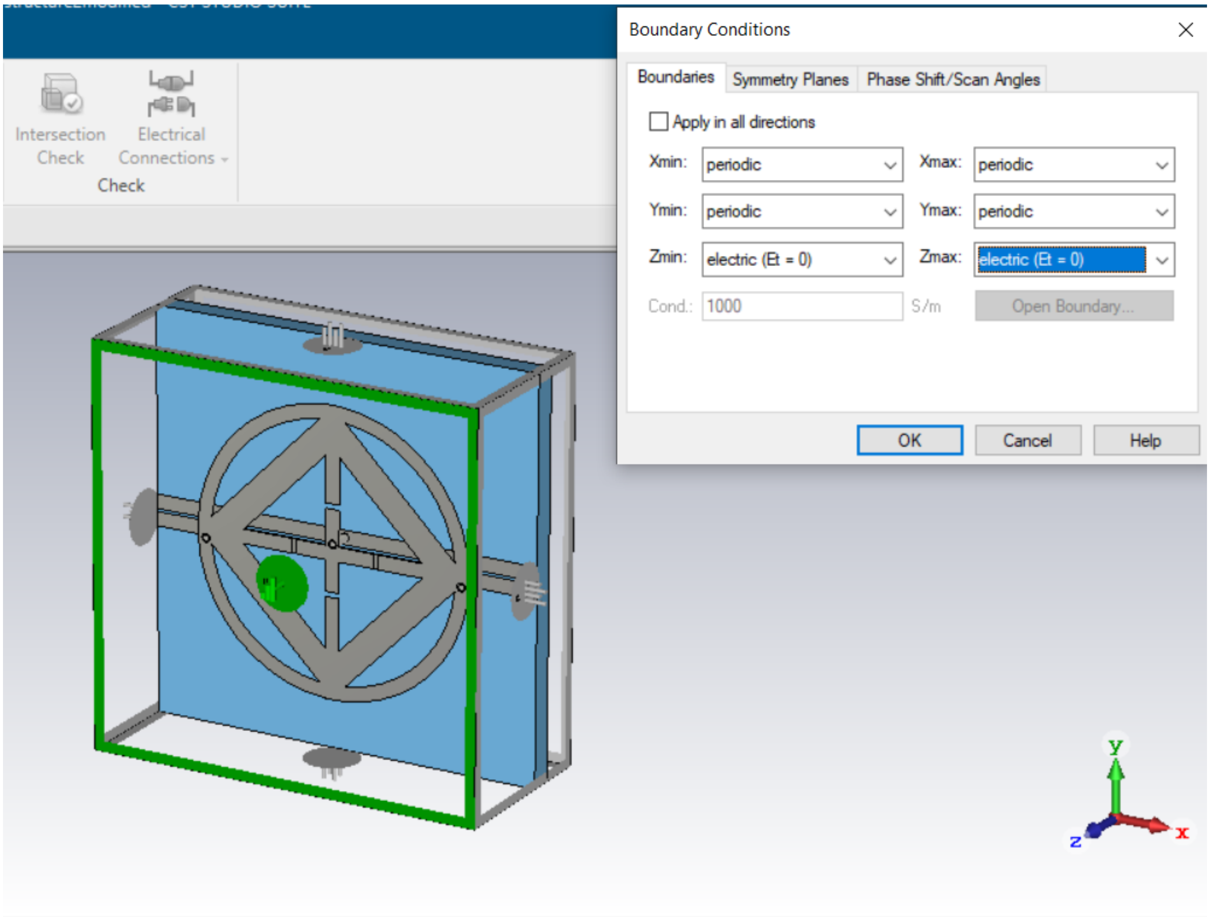


figure 4.9 Boundry condition

CHAPTER 5

RESULTS

Result of structure with Cut-Slots

In the final chapter of the thesis the simulation of results is presented by using 1-D dispersion diagram. And the result is numerically analysed using ten modes to observe the behaviour of the propagation over 18 points corresponding to phaseX that are taken between 5 to 175 and not from 0 to 180 just to avoid the calculations near the band edges. The selected boundary condition is electric-electric from zmin and zmax and all the other boudry conditions are kept periodic.

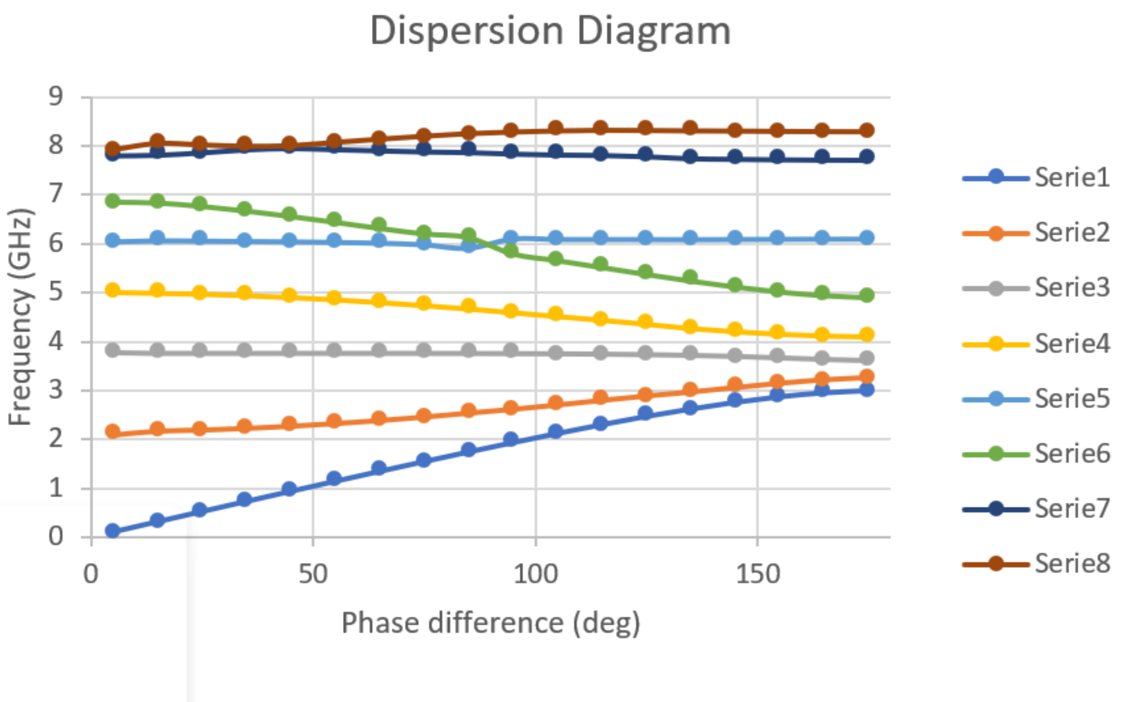


Figure 5.1: Dispersion Diagram

In the DD there is Frequency in GHz at Y-axis and the phase difference is at X-axis. By looking closely we can see that the green line and blue line in the graph are intersecting each other that corresponds to modes with the same phase velocity. Such condition allows for example interchanging energy between modes.

Conclusion

In the thesis the 'Numerical analysis of periodic structures' is presented in which two structure are analyzed over one base structure using FR-4 substrate layer, at top and bottom the additional dielectric layer. The structure further incorporates two micrsostrip lines three vias and four cut-slots. The microstrip lines are connected to the main structure by using via-holes and then the result simulation for the structure with four cuts is performed with the boundary condition for zmin and z max with electric-electric boundary condition, while the other conditions and kept periodic. The common modes are detected that are propagating in the same fashion. Result is presented in the form of dispersion diagram in which the propagation of waves in frequency vs phaseX is represented.

In the future PIN diodes can be used in these cuts for further experimentations and to observe the behaviour of the waves propagation in a timely variable structures.

REFERENCES

[1] Matekovits, Ladislau, Michale Heimlich, and Karu P. Esselle. "Tunable periodic microstrip structure on GaAs wafer." *Progress In Electromagnetics Research* 97 (2009): 1-10.

[2] Matekovits, L., Esselle, K. P., Bercigli, M., & Guidi, R. (2014). Efficient numerical analysis of a periodic structure of multistate unit cells. *International Journal of Antennas and Propagation*, *2014*.

[3] Yang, H. Y. D. (1999). Theory of microstrip lines on artificial periodic substrates. *IEEE transactions on microwave theory and techniques*, *47*(5), 629-635.

[4] Xu, R. J., & Lin, Y. S. (2022). Actively MEMS-based tunable metamaterials for advanced and emerging applications. *Electronics*, *11*(2), 243.

[5] Bacigalupo, A., De Bellis, M. L., & Misseroni, D. (2020). Design of tunable acoustic metamaterials with periodic piezoelectric microstructure. *Extreme Mechanics Letters*, *40*, 100977.

[6] Kubacki, R., Lamari, S., & Rudyk, K. (2016, May). The dispersion diagram used for periodic patterned microstrip antenna analysis. In *2016 21st International Conference on Microwave, Radar and Wireless Communications (MIKON)* (pp. 1-4). IEEE.

[7] Anwar, R. S., Mao, L., & Ning, H. (2018). Frequency selective surfaces: a review. *Applied Sciences*, *8*(9), 1689.

[8] Alex-Amor, A., Palomares-Caballero, A., Mesa, F., Quevedo-Teruel, O., & Padilla, P. (2021). Dispersion analysis of periodic structures in anisotropic media: Application to liquid crystals. *IEEE Transactions on Antennas and Propagation*, *70*(4), 2811-2821.

[9] Veselago, V. G. (1967). Electrodynamics of substances with simultaneously negative and. *Usp. fiz. nauk*, *92*(7), 517.

[10] Pendry, J. B., Holden, A. J., Robbins, D. J., & Stewart, W. J. (1999). Magnetism from conductors and enhanced nonlinear phenomena. *IEEE transactions on microwave theory and techniques*, *47*(11), 2075-2084.

[11] Bukhari, S. S., Vardaxoglou, J., & Whittow, W. (2019). A metasurfaces review: Definitions and applications. *Applied Sciences*, *9*(13), 2727.

[12] Cai, W., & Shalaev, V. M. (2010). *Optical metamaterials* (Vol. 10, No. 6011). New York: Springer.

[13] De Sabata, A., & Matekovits, L. (2012). Reduced complexity biasing solution for switched parallel plate waveguide with embedded active metamaterial layer. *Journal of Electromagnetic Waves and Applications*, *26*(14-15), 1828-1836.

[14] Bideskan, M. Z., Forooraghi, K., & Atlasbaf, Z. (2020, August). Determination of Floquet's Modes in Graphene-Based Periodic Structures Using Method of Lines. In *2020 28th Iranian Conference on Electrical Engineering (ICEE)* (pp. 1-5). IEEE.

[15] Matekovits1, «Width-Modulated Microstrip Line Unit Cell: A Quasi-Periodic Combinational Sequence for Holographic Array Applications,» in *Asia-Pacific Microwave Conference 2011*, 2011.

[16] Cui, T. J., Li, L., Liu, S., Ma, Q., Zhang, L., Wan, X., ... & Cheng, Q. (2020). Information metamaterial systems. *Iscience*, *23*(8), 101403.

[17] Glybovski, S. B., Tretyakov, S. A., Belov, P. A., Kivshar, Y. S., & Simovski, C. R. (2016). Metasurfaces: From microwaves to visible. *Physics reports*, *634*, 1-72.

[18] Oliveri, G., Werner, D. H., & Massa, A. (2015). Reconfigurable electromagnetics through metamaterials—A review. *Proceedings of the IEEE*, *103*(7), 1034-1056.

[19] Smith, D. R., Padilla, W. J., Vier, D. C., Nemat-Nasser, S. C., & Schultz, S. (2000). Composite medium with simultaneously negative permeability and permittivity. *Physical review letters*, *84*(18), 4184.

[20] Gao, X., Yang, W. L., Ma, H. F., Cheng, Q., Yu, X. H., & Cui, T. J. (2018). A reconfigurable broadband polarization converter based on an active metasurface. *IEEE Transactions on Antennas and Propagation*, *66*(11), 6086-6095.

[21] Zhang, L., Yang, G., Wu, Q., & Hua, J. (2012). A novel active frequency selective surface with wideband tuning range for EMC purpose. *IEEE Transactions on Magnetics*, *48*(11), 4534-4537.

[22] Supplies, M. S. E. (2021). List of thermal expansion coefficients (CTE) for natural and engineered materials.