"Analysis of Trapped Oscillation Modes in Magnetized Plasma Photonic Crystal using One-Dimensional Modeling"

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Submitted by**:**

Tanvi Mittal

Roll No: 801463029

Under the guidance of**:**

Dr. Rana Pratap Yadav

(Assistant Professor, ECED)

ELECTRONICS AND COMMUNICATION ENGINEERING DEPARTMENT

THAPAR UNIVERSITY

(Established under the section 3 of UGC Act, 1956)

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CERTIFICATE

I hereby certify that the work which is being presented in the Dissertation entitled "**Analysis of Trapped Oscillation Modes in Magnetized Plasma Photonic Crystal using One-Dimensional Modeling**" is an authentic record of my study carried out as requirement for the award of degree of Master of Engineering in Wireless Communications at Thapar University, Patiala, under the supervision of **Dr. Rana Pratap Yadav, Assistant Professor,** Electronics and Communication Engineering Department (ECED). The matter presented in the dissertation has not been submitted in any other University/Institute for the award of degree.

Tanvi Mittal

Date: 28/06/2016

Tanvi Mittal

Roll No. 801463029

It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

Date: 28/06/2016

Dr. Rana Pratap Yadav

Assistant Professor, ECED

Thapar University, Patiala

Countersigned by

Dr. Sanjay Sharma

Professor and Head (ECED)

Thapar University, Patiala

Dr. S.S. Bhatia

Dean, Academic Affairs

Thapar University, Patiala

ABSTRACT

Dissertation presents the analysis and simulation of magnetized binary plasma photonic crystal (PPC) using 1-D mathematical modeling, where trapped oscillation in photonic bandgap (PBG) has been highlighted using dispersion relation and transmittance characteristics. A comparative study on binary and ternary magnetized PPC has also been presented based on the PBG characteristics. The PPC constitutes the periodic structure of plasma and dielectric layers, where the propagation of electromagnetic waves depends on effective plasma frequency (EPF). It is the lowest frequency of wave which can pass through the PPC structure. The presence of plasma layer in PPC provides wide tunability of EPF and this enables to tune the PPC electronically for desired PBG in a very fast manner by varying magnetic field, electronic concentration and thickness of plasma layer. This theory is explained in detail in thesis through the analysis of binary and ternary magnetized PPC and it is found that the value of EPF is lower for ternary PPC as compared to the binary one and this difference could be more significant when more number of layers is structured. Also, the presence of static magnetic field provides extra-ordinary mode in plasma that yields to trapped oscillations and introduces undesirable discontinuity in the PBGs. This is found to be mainly dependent on applied magnetic field, electronics concentration and hybrid frequency and can be shifted to any other position in a prescribed frequency band by having suitable values of these parameters. This property in PPCs can be utilized for the design of filters in millimeter range and in military applications, viz. to prevent the spoofing of signals from enemies, during communication.

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Date: _______ Tanvi Mittal

Place: Patiala M.E. (801463029)

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LIST OF ACRONYMS

EM	Electromagnetic
PC	Photonic Crystal
PBG	Photonic Bandgap
EBG	Electronic Bandgap
MDPC	Metal-Dielectric Photonic Crystal
SDPC	Superconductor-Dielectric Photonic Crystal
PPC	Plasma Photonic Crystal
EPF	Effective Plasma Frequency
1-D	One-Dimensional
TEM	Transverse Electromagnetic
2-D	Two-Dimensional
FDTD	Finite Difference Time Domain
TE	Transverse Electric
TM	Transverse Magnetic
Fig	Figure
GHz	Giga Hertz
T	Tesla
Cm	Centimeter
Mm	Millimeter
MATLAB	Matrix Laboratory
X-mode	Extra-ordinary mode
UHF	Ultra-High Frequency
SHF	Super High Frequency
EHF	Extremely High Frequency

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Preamble

Recently, the plasma based technologies provide many advantages over the established technologies due to the rapid growth in the use of plasma for the industrial applications. Plasma is known as the fourth state of matter after solid, liquid and gas and its material properties like electric permittivity and magnetic permeability, which are the fundamental characteristics, that determine the propagation of EM waves in matter, can be tuned by changing the plasma parameters for EM radiations.

Photonic crystal (PC) is a periodic optical structure which acts as an electromagnetic medium and provides a photonic bandgap (PBG) in which waves of certain frequency ranges are not allowed to propagate. PCs are the periodic structures with multiple layers and possess photonic bandgaps (PBGs), formed because of Bragg scattering in the multi-layered structure. PBGs are similar to the electronic bandgap (EBGs) in semiconductor materials and solid. The work related to photonic crystals (PCs) over the last two decades pulled the researchers to work in this field. In the early days, conventional PCs made of metallic materials or dielectric was of much interest. Later on, PCs with composite structure of different materials like metal-dielectric photonic crystal (MDPC) and superconductor-dielectric photonic crystal (SDPC) have been reported where photonic bandgaps are found to be tuned with the temperature and magnetic field, because permittivity of these materials is sensitive to these two factors. In SDPC, transmission of EM wave is enhanced in visible region due reduction of conductive losses [1-7].

Due to the unique features possessed by PCs, the field related to solid state and optical physics are also moving towards them and the applications are also expanding as in frequency filter, frequency convertor etc. This has important scientific and engineering applications such as control of light emission and propagation. PCs can be adapted as Filters, Waveguides, Optical switches, Sensors, Frequency converters and advances in microwave circuits.

The PBG depends on the properties and configuration of material used in fabrication of the PC. Based on the structural configuration, these can be classified into one-dimensional, two-dimensional (binary) and three-dimensional (ternary) PCs. In early stage, PCs have been reported as periodically structured layers of dielectric and/or metallic materials [8]. In these, parameters determining the position and the width of the PBGs, such as permittivity and lattice constant, are difficult to change once the structure has been established and hence, the PBG remains fixed. PCs with composite structure of different materials like metal-dielectric photonic crystals (MDPCs) and superconductor-dielectric photonic crystals (SDPCs) have also been studied. In these PCs, PBGs are tuned by varying temperature and magnetic field [2,4]; but it has very limited scope. The tunability in the structure was obtained in a significant manner as research extended to plasma photonic crystals (PPCs).

The PPC is a periodic structure made of alternate layers of thin plasma and dielectric material. PPCs were first introduced in 2004 by Hojo and Mase [9]. Many investigations have been reported on the wave properties of the plasma photonic crystals [10–24]. This structure can be effectively tailored to obtain useful characteristics such as: highly tunable dispersion, to slow down light waves in controllable manner, operation at wide wavelength range and optical functions such as switching and sensing [25-26]. The propagation of electromagnetic wave in PPCs depends on the effective plasma frequency, which is the lowest frequency that can pass through the structure. The detailed analyses on EPF, dispersion relation and reflectance of PPCs have been presented in earlier studies [16-18,20,27-28].

The properties associated with these PPCs are extremely controllable and have the same characteristics as that of conventional PCs and plasma. This is why PPCs attract attention of many researchers and the application associated with the PCs also moved researchers to this side. Hojo [9] studied about the effect of dielectric constant of dielectric media, effect of plasma density and thickness of plasma layer on the dispersion characteristics. Researchers analyzed various aspects of 1D-PPCs, like Guo Bin [29] analyzed the dispersion relation of binary 1D-PPCs considering the collision effect in plasma with obliquely incident EM waves. Also, Prasad et al. [30-32] studied about ternary 1D-PPCs. Researchers analyzed about the reflection and transmission coefficient, the dispersion characteristics, modal propagation characteristics of 1D-

PPCs and it was found that these properties could be controlled by external magnetic fields, plasma density, plasma width, collision frequency and permittivity of dielectric materials [33-40].

This structure works at microwave band and can be effectively tailored to obtain useful characteristics broadband operation and optical functions such as sensing [25-26]. PPCs provide these interesting characteristics due to its equivalent permittivity dependency on the frequency of the incident electromagnetic wave and other parameters like electronic concentration.

1.2 Outline to Thesis

The dissertation is divided into six different chapters. Chapter-1 gives the introduction about the PPC; its background, types and applications are highlighted. In chapter-2, we provide the literature survey, i.e., all the papers that have been published related to the presented work. The mathematical model of binary-PPC has been analyzed in chapter-3 which helps in obtaining its structure characteristics in terms of dispersion relation. Chapter-4 explains the dispersion relation characteristics for ternary-PPC using 1-D mathematical model and results have been compared with binary one. In chapter-5, the same analysis, as in chapter-3, has been carried out for binary-PPC for higher frequency range upto 140GHz and non-linearity in the characteristics has been studied in terms of dispersion relation and transmittance characteristics. Finally, the concluding remarks and future scope has been presented in chapter-6.

Chapter-2 explains the work that has already been done related to the work presented in the dissertation. It is useful in gaining the detailed knowledge of the topic and in learning a sustainable approach to carry out the defined work.

Chapter-3 provides the detailed analysis of binary-PPC using one-dimensional mathematical modeling by transfer matrix method. The dispersion relation characteristics have been studied for different plasma parameters like plasma frequency, plasma density and plasma width and other parameters like external magnetic field and angle at which the propagating wave is incident on the structure. The analysis shows that the photonic band structure can be effectively tuned by electronically varying any of these parameters such that we can easily switch from one PBG to another without any physical change in the structure.

Chapter-4 explains the mathematical model of ternary-PPC using one-dimensional analysis and the dispersion relation has been characterized for different extrinsic and intrinsic parameters like electronic concentration, external magnetic field and thickness of plasma layer. The results are compared to the binary-PPC and the effect of insertion of extra dielectric layer in ternary structure is shown.

Chapter-5 gives the analysis of trapped oscillations in magnetized binary-PPC that leads to non-linearity in the dispersion relation and transmittance characteristics in the specific frequency range. This non-linearity is found to be effectively reduced for low electronic concentration and for non-magnetized plasma.

Chapter-6 gives the conclusion and future scope. It focuses on the work that can be carried out in future based on the properties and applicability of the structures studied.

CHAPTER 2

LITERATURE SURVEY

Various research papers have been studied in order to find the appropriate topic for the dissertation. The following papers are related to the selected topic and have been studied based on the previous work done and the applications. Literature survey has helped in getting detailed understanding and learning a better approach to carry out the required work.

C. S. Gurel *et al.* [6] analyzed the reflectance, transmittance and absorption characteristics when a wave is made incident on the plasma with different density profiles such as linear and sinusoidal. Electronic concentration and magnetic field were varied and it was found that reflectance properties were in a narrow band of frequencies while the absorption characteristics were in broad band of frequencies that could be tuned to desired level. Thus, the layer of plasma can be helpful as an absorbing layer that helps in shielding. This plasma layer could absorb the power of the incident electromagnetic wave which increases with increase in thickness of the plasma layer. As the absorption increased, the reflectance decreased since the reflected power decreased. Also, the absorption characteristics were studied to be highly influenced by the collision frequency and plasma density.

In this article, **P. Pintus** *et al.* [7] considered the photonic crystal with impurities and using one-dimensional analysis, evaluated its spectrum, photonic band structure and energy levels. Refractive index and scattering matrices were derived using the theoretical analysis and these defined the characteristics of the photonic crystals using Maxwell's equations. Electromagnetic wave in TEM mode was made to propagate through the structure of finite lattice constant and found the refractive indices using the eigen values in the photonic band structure. These were compared to scattering coefficients to verify the results.

Hojo *et al.* [9] studied one-dimensional structure of PPC and its dispersion relation characteristics using EM waves. These characteristics were drawn using Maxwell equations. It was found that cut-off frequency and band-gaps are obtained when 1-D analysis of EM wave is done, when passed through the PPC structure. It was also found that the frequency band gap increased when plasma density was increased. Also, the band gap became larger with increase in width of the plasma layer. The study suggested that in the range of millimeter waves, such structures can be utilized as frequency filters.

P. Mahto *et al.* [12] evaluated the transfer matrix method for the one-dimensional plasma photonic crystals made of periodically structured layers of plasma and dielectric. The structure properties are calculated for different values of lattice constant, i.e., finite and infinite periodicity. The structure characteristics were determined with respect to plasma parameters such as thickness of plasma layer, its density and number of layers of plasma. Reflectance and transmittance was evaluated in terms of these parameters. It was observed that photonic band gap exists for any number of lattice constants, i.e., as low as one and as high as infinite number of periodically structured layers. The photonic band gaps were shown to be dependent on the width and density of plasma layer and increased with increase in plasma density whereas it decreased with increase in thickness of plasma layer.

Wei Li *et al.* [13] presented the theory based on plasma photonic crystal. They suggested that the permittivity of different layers of PPC is periodic and can control the transmission of electromagnetic wave in the structure. It is shown to be in similarity with other types of photonic crystals. This property was discussed to increase the frequency range of operation and thus, the efficiency of the structure. It was also proposed that the permittivity of the array of different layers could be varied from a value as high as 10 to an imaginary value.

H. Hojo *et al.* [14] evaluated the transmittance for 1-D plasma photonic crystals when an electromagnetic wave is considered to be incident normal to the surface of the structure. For magnetized plasma, it was found out that the transmittance is dependent on the plasma density and physical structure of the PPC. It was studied that a small change in the structural parameter would vary the transmittance to a large amount.

The photonic band gaps in PPCs were also studied and were found to vary with variation in structural parameters. This property of PPCs is helpful in designing of filters in millimeter range.

V. Kumar *et al.* [15] studied the periodically structured layers of plasma and dielectric such that their characteristics were presented in the form of reflectivity, band structures and effective group indices. Different dielectrics were chosen for comparison such as Sio_2 and TiO_2, respectively. Transfer matrix method has been used to study the structures and it was found that the photonic band gaps are the increasing function of plasma width. It was found that in case of $SiO_{2,}$ the reflection coefficient was maximum for higher frequency range, and in case of $TiO_{2,}$ the reflection was maximum for lower frequencies. The effective group index for such structures is found to be negative which has very high values. Thus, it was inferred that plasma photonic crystals can be utilized as frequency selectors and filters when the structural parameters are appropriately set.

W. Fan *et al.* [16] obtained a dielectric barrier discharge between liquid electrodes to design plasma photonic crystal in one-dimension. Helmholtz equation was used to evaluate the dispersion relation of the crystal structure. The photonic band structures were studied with respect to the periodicity, electronic concentration and the filling factor, experimentally. It was found that the band gap increases when the filling factor increased. The band gap width and starting point were observed to be increased with increase in the electronic concentration and decreased when lattice constant would increase.

L. Yang *et al*. [17] analyzed 1-D PPC through modified Finite difference time domain method, when an electromagnetic wave is obliquely incident over the structure. This method has been applied to study the PBG characteristics for different angles of incidence and the reflection coefficients have been calculated for the given structure. Precise and effective results were obtained with this method compared to 2-D FDTD method. Thus, this modified method is much efficient and replaces 2-D FDTD method, providing much improvement in the results. Transmittance has also been analyzed for the same structure for different angles of incidence. Both TE and

TM waves have been considered for the oblique incidence on the PPC structure for the analysis of reflection coefficient and transmission characteristics. The same method has also been applied to calculate the scattering characteristics of the electromagnetic waves in the PPC for different angles of incidence.

X. Kong *et al.* [18] studied the properties of plasma photonic structure using one-dimensional analysis by transfer matrix method. Modification in structure properties was evaluated for the given PPC structure. Effect of width of plasma and dielectric layers and frequency of plasma layer was studied. It was found that both these parameters influenced the wave properties of the structure and the band position and cut-off frequency varied with variation of thickness of layers and the plasma frequency. Photonic band structure was influenced by the variation in width of the plasma and dielectric layer; however there was change in cut-off frequency with variation in the frequency of plasma layer. It was observed that modification in plasma frequency was more effective on the results than the modification in width of the constituent layers. When the lattice constant of the structure was increased, better quality factor was obtained. Transmittance of the wave was also plotted, that was modified by the structure parameters.

Q. Zhu [19] studied the photonic band structures analytically for photonic crystals using one-dimensional analysis. The effect of thickness of constituent materials on the photonic band structure was evaluated and it was found that the band gaps could be varied effectively by varying the width of the layers. Thus, the range of frequencies of photonic band structures is found to be effectively widened by simply varying the thickness of the material of the structure.

L. Qi *et al.* [20] studied the reflectance for magnetized plasma photonic crystal using one-dimensional analysis of transfer matrix method. The structure was evaluated for different parameters like angle of incidence, externally applied static magnetic field and the collision frequency. Reflectance characteristics of the structure showed that the band gap width and location can be adjusted highly with angle of incidence for small values of magnetic field; however there is a little change for large value of magnetic field. It was also shown that collision frequency has negligible effect on reflectance and transmittance. For the higher value of lattice constant, the reflectance is ideal with smaller gaps.

Bin Guo *et al.* [21] considered transfer matrix method to evaluate the photonic band structure of the plasma photonic crystal and derived the dispersion relation for different cases such as linear, non-uniform and exponential distribution. It was shown that frequency band gaps and cut-off frequency is present for all the distributions with reflectance and absorbing characteristics. Also, an increase in photonic band gap was realized with increase in electronic concentration of the plasma layer.

S. Prasad *et al.* [23] considered a single period of plasma and dielectric array to evaluate the dispersion relation using matrix evaluation. The calculations were performed for different profiles of density of plasma, namely, linear profile and exponential profile. The results of these density profiles were compared to plasma with uniform density. Dispersion characteristics were studied for different parameters like photonic band gap width. It was shown that as for the exponential profile, the bandwidth is always greater than that for linear profile. Also, for the increasing angle of incidence the photonic band gap width is increased and transferred to frequency with higher value. It was shown that the band gap number is an increasing function of plasma width.

Elahe Ataei *et al.* [24] considered 1-D PPC with four different layers periodically structured one after the other. These were Plasma1, MgF2, Plasma2 and Glass; with different frequencies of two plasma layers. The researchers analyzed the Photonic band gap characteristics for TE and TM and calculated the dispersion relation for the given structure. The effect was studied on the PPC structure in the presence of static magnetic field by calculating the effective permittivity of the respective layers, analytically. It was observed that the width of the band gap increased as applied magnetic field was increased. Also, it was shown that with the increase in the magnetic field value, the bandwidth of the gap shifted to higher frequency. However, it was inferred that beyond a certain limit increase in magnetic field value has no effect on dispersion relation characteristics. The effect of different angles of incidence was also calculated for TE as well as TM-polarized waves on the structure. It was found that for an angle of incidence up to 66^0, the photonic band gap width increases for TE polarized wave and decreases for TM-polarized wave. When the angle of incidence is increased from 66^0 to 89^0, then band gap width increases for both the types of waves. Also, the width is shown to be affected by different values of plasma frequency. The results pointed out that the dispersion relation can be controlled by static magnetic field, angle of incidence and different plasma frequencies that could help in designing the filters and fibers.

S. Prasad *et al.* [26] calculated the dispersion relation by transfer matrix method using the Maxwell's equations for one-dimensional plasma photonic crystals. Refractive index for the same structure was also studied. The effect of different plasma parameters such as plasma frequency and density and thickness of plasma layer is calculated on the photonic band gap. It was found that band gap width and starting point shifted to higher frequency with increase in plasma density. Also, the cut-off frequency increased for increasing thickness of plasma layer. The comparison was also made between one-dimensional photonic crystal and one-dimensional plasma photonic crystals for binary and ternary structures. It was inferred that the introduction of plasma layer in PPC structure improved the phase-matching and provided extra adjustability in the structure as compared to the photonic crystals.

L. Qi [27] studied the characteristics of one-dimensional plasma photonic crystals for an obliquely incident wave on the structure. The wave was considered to be electromagnetic wave that was made to pass through the structure of magnetized plasma layered periodically with dielectric. Dispersion relation characteristics and transmittance were calculated using the matrix method as a function of various parameters like static magnetic field, permittivity of dielectric layer, different angles of incidence and collision frequency. It was shown that the band gap width can be adjusted by varying the external magnetic field and angle of incidence. The effective plasma frequency decreases with increase in magnetic field and has a negligible effect when collision frequency is varied. Increase in permittivity constant of the dielectric caused more gaps. When the collision frequency was increased beyond a certain value, the reflectance and transmittance decreased to a great extent.

C. J. Wu *et al.* [28] considered an array of 1-D structure of superconductor-dielectric photonic crystal (SDPC) and analyzed the effective plasma frequency of the given structure. The effective plasma frequency has been shown less as compared to the frequency of superconductor. Different values of width of dielectric layer were considered and it was observed that effective plasma frequency is a decreasing function of the dielectric width. The effect of temperature and filling factor was also shown on the structure and it was observed that a higher value of EPF was obtained when the value of temperature was decreased.

Bin Guo [29] analyzed the plasma photonic crystals for electromagnetic waves incident at some angle on the structure and calculated the dispersion relation using transfer matrix method. The dispersion relation was found to be dependent on the plasma parameters like width of plasma layer, density and the lattice of the structure. It was observed that the photonic band gaps are the increasing function of the thickness of plasma layer and the density. For the higher values of permittivity, the band gap becomes smaller. When the angle of incident is normal to the structure, the band gap becomes smaller.

S. Prasad *et al.* [30] observed the dispersion characteristics for one-dimensional ternary plasma photonic crystal using Maxwell’s equations. Group velocity and refractive indices were also studied for the structure based on the Kronig-Penny model. It was shown that similar to binary PPC structures, ternary PPCs have frequency band gaps and cut-off frequencies. It was studied that photonic band gap increased with increase in frequency and thickness of plasma layer. It was also shown that the structure has better structure properties as compared to the binary PPC because of the presence of extra dielectric layer. Also, the effective group index was observed to be the decreasing function of frequency of plasma layer and it increased for the thickness of plasma layer greater than that of the dielectric layer.

S. Prasad *et al.* [31] considered two structures of ternary plasma photonic crystals and analyzed the dispersion relation characteristics. The third dielectric layer in the ternary PPC was ZnS and MgF_2 for two different cases. Electromagnetic wave was propagated through these structures and dispersion characteristics were evaluated using Maxwell's equations. It was shown that the characteristics are dependent upon plasma parameters like frequency, thickness of plasma layer and upon the thickness of dielectric layer. The band gap width was observed to be increased when the thickness of plasma layer was increased. This width is even larger foe the structure with ZnS as compared to the structure having dielectric $MgF_{2.}$ Thus, it was evaluated that ternary PPC structure having ZnS as the dielectric layer has better filtering properties because of broad band of applications.

X. Xu *et al.* [33] analyzed the structures of metallic-dielectric photonic crystals (MDPC) in one-dimension. Photonic band gaps were studied and effective plasma frequency was determined theoretically. The effective plasma layer was studied with respect to the width of dielectric layer and it was found that it is a decreasing function of width of the dielectric layer. It was inferred that as the thickness of dielectric layer is increased, the frequency decreases down to extremely low points. These low frequency points are far infrared regions and frequencies below that point. It was also found that varying the width of the metallic layer in MDPC has no effect on effective plasma frequency.

Here, **J. Manzanares-Martinez** [36] derived an expression of effective plasma frequency for one-dimensional metal-dielectric photonic crystal (MDPC), containing periodically structured layers of metal and dielectric having some periodicity. The analytical study on effective plasma frequency revealed its dependency on constituent materials. Photonic band structure was also analyzed for the calculation of cut-off frequency. Absorption characteristics were determined for the one-dimensional analysis of the MDPC structure.

C. J. Wu *et al.* [38] compared the characteristics of plasma photonic crystals for binary and ternary structures with respect to effective plasma frequency. For both binary and ternary structures, it was observed that the effective plasma frequency is always less than the bulk plasma frequency. For the binary structure, it was shown that the effective plasma frequency increased for the increasing value of electronic concentration and plasma width; and decreased for the increasing value of width of dielectric. When compared to the ternary PPC, it was observed that effective plasma frequency of binary was higher. The decrease in effective plasma frequency was inferred because of the addition of extra dielectric layer in the structure.

H. T. Hsu *et al.* [39] considered the ternary magnetized structure of plasma photonic crystal and calculated effective plasma frequency. It was shown that it decreases with increase in magnetic field. It illustrated that angle of incidence has a negligible effect on effective plasma frequency when a TM polarized wave was incident on the structure. The effective plasma frequency was shown to be an increasing function of plasma width. The transmission characteristics were plotted to illustrate the results for the PPC structure.

T. C. King *et al.* [40] considered the structure of one dimensional plasma photonic crystal and evaluated effective plasma frequency for the given structure. The band structure of the PPC was evaluated to calculate the effective plasma frequency. The effective plasma frequency was given as a function of externally applied magnetic field and it was shown that it decreases with increase in value of magnetic field. Thus, PPC could be considered like a dielectric in the presence of large magnetic field. Also, it was observed that effective plasma frequency increases with increase in electronic concentration and width of plasma. In case of magnetized PPC structure, effective plasma frequency increases with increase in incident angle.

CHAPTER 3

Analysis of Binary PPC using 1-D Mathematical Modeling

3.1 Introduction

This chapter presents the analysis of binary magnetized plasma photonic crystal using 1-D modeling in the frequency range 1-50GHz. The PPC is periodically structured with plasma layer 'A' and dielectric layer of Glass 'B', with their respective thickness as d_p and d_d, as shown in Fig.3.1. It is structured such that the two layers are periodic about $\Delta = (d_p + d_d)$, where Δ is known as the lattice constant. The relative permittivity of the layers A and B are taken as ε_p and ε_d, with refractive indices n_p and n_d, respectively. Here, dispersion relation characteristic of PPC has been studied using 1-D mathematical model for the different extrinsic and intrinsic parameters, such as the electronic concentration, static magnetic field, thickness of plasma layer, angle of incidence and collision frequency.

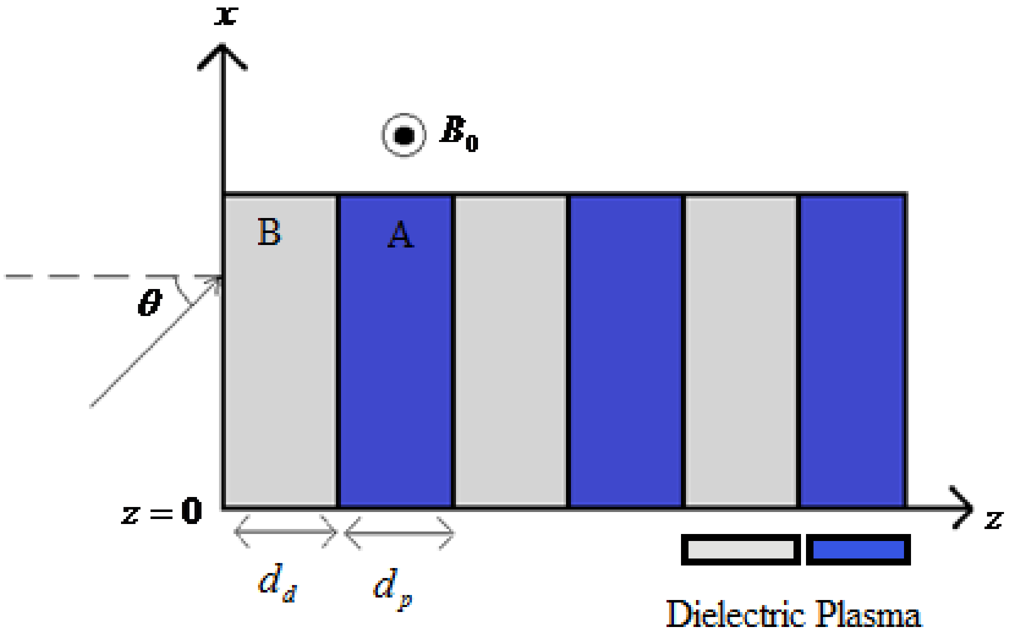

Fig. 3.1 Schematic of 1-D model of magnetized plasma photonic crystal (PPC)

3.1.1 Mathematical Modeling

A TM-wave propagating along the z-direction is considered to be incident from free space to the left plane boundary of the PPC with an angle θ at the z=0. This TM wave propagating in z-direction satisfies the Helmholtz equation, i.e., given by

$$\left[\frac{d^2}{dz^2}+k_0^2\varepsilon(z)\right]H(z)=0 \tag{3.1}$$

where, $k_0 = \omega/c$ is the wave number of the free space.

General solution of $H(z)$ in equation (3) is given by

$$H(z)=\left\{a_m e^{ik_{dz}z}+b_m e^{-ik_{dz}z}, m\Delta < z < m\Delta + d_d\right. \tag{3.2a}$$

$$\left\{c_m e^{ik_{pz}z}+d_m e^{-ik_{pz}z}, m\Delta + d_d < z < (m+1)\Delta\right. \tag{3.2b}$$

where, $m = 0,\ \pm1,\ \pm2$ ...so on and b_m, d_m and a_m, c_m are the wave amplitudes in the forward and the backward direction, respectively; k_{dz} and k_{pz} are the normal components of the wave number given by [8]:

$$k_{dz}=\sqrt{k_0^2 n_d^2-\beta^2}=k_0 n_d \cos(\theta_d)=\omega/c\,\sqrt{\varepsilon_d}\cos(\theta_d) \tag{3.3a}$$

$$k_{pz}=\sqrt{k_0^2 n_p^2-\beta^2}=k_0 n_p \cos(\theta_p)=\omega/c\,\sqrt{\varepsilon_p}\cos(\theta_p) \tag{3.3b}$$

Here, θ_d and θ_p are the angle of incidence of the wave in the dielectric and plasma layer, respectively.

Each of the section A and B can be represented by transmission matrix M_d and M_p that are given by [20]:

$$M_d=\begin{pmatrix}\cos(k_{dz}d_d) & -\frac{j}{\eta_d}\sin(k_{dz}d_d)\\ -j\eta_d\sin(k_{dz}d_d) & \cos(k_{dz}d_d)\end{pmatrix}, \tag{3.4}$$

$$M_p = \begin{pmatrix} \cos(k_{pz}d_p) + \varepsilon_{21}\tan\theta_p \sin(k_{pz}d_p) & -\dfrac{j}{\eta_p}\left[1+\left(\varepsilon_{21}\tan\theta_p\right)^2\right]\sin(k_{pz}d_p) \\ -j\eta_p \sin(k_{pz}d_p) & \cos(k_{pz}d_p) - \varepsilon_{21}\tan\theta_p \sin(k_{pz}d_p) \end{pmatrix} \tag{3.5}$$

where, η_p, η_d are wave impedance of region A and B, and ω_c is cyclotron frequency and its values are given by:

$$\eta_p = \sqrt{\varepsilon_{TM}}\left(\sqrt{\varepsilon_0/\mu_0}\right)\left(1/\cos\theta_p\right),$$

$$\eta_d = \sqrt{\varepsilon_d}\left(\sqrt{\varepsilon_0/\mu_0}\right)\left(1/\cos\theta_d\right).$$

Also [28],
$$\varepsilon_{TM} = \frac{\left[\omega(\omega + j\gamma) - \omega_p^2\right]^2 - \omega^2\omega_c^2}{\omega^2\left[(\omega + j\gamma)^2 - \omega_c^2\right] - \omega\omega_p^2(\omega + j\gamma)}$$

$$\varepsilon_{21} = \frac{-\omega_p^2\omega_c}{\omega\left[(\omega + j\gamma)^2 - \omega_c^2\right] - \omega_p^2(\omega + j\gamma)}.$$

ε_{TM} is the effective permittivity of plasma and ε_{21} is the relative permittivity taken into consideration when wave is incident obliquely from dielectric region to plasma region.

Now, wave transmission through lattice can be written as,

$$\begin{bmatrix} a_{m-1} \\ b_{m-1} \end{bmatrix} = M \begin{bmatrix} a_m \\ b_m \end{bmatrix} \tag{3.6}$$

where, b_{m-1} and a_{m-1} are forward and reflected wave amplitude at left boundary of the lattice and b_m and a_m are forward and reflected wave amplitude of the transmitted wave and M is known as the transmission matrix. It is given by the multiplication of transfer matrices of the two cascaded layers of plasma and dielectric and evaluated in terms of the ABCD parameters as:

$$M = M_d M_p = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{3.7}$$

Now, the dispersion relation can be determined by the half trace of the transfer matrix M that is given by

$$\cos(k\Delta) = \frac{1}{2}(A + D) \tag{3.8}$$

where, k is the Bloch wave vector used to describe the conduction of an electron inside the PPC structure; A and D are the diagonal elements of transmission matrix obtained by the matrix multiplication of (3.4) and (3.5) as:

$$A = \cos(k_{dz}d_d)\cos(k_{pz}d_p) + \varepsilon_{21}\tan\theta_p\cos(k_{dz}d_d)\sin(k_{pz}d_p) - \frac{\eta_p}{\eta_d}\sin(k_{dz}d_d)\sin(k_{pz}d_p) \tag{3.9}$$

$$D = \cos(k_{dz}d_d)\cos(k_{pz}d_p) - \varepsilon_{21}\tan\theta_p\cos(k_{dz}d_d)\sin(k_{pz}d_p) - \frac{\eta_d}{\eta_p}\left[1 + \left(\varepsilon_{21}\tan\theta_p\right)^2\right]\sin(k_{dz}d_d)\sin(k_{pz}d_p) \tag{3.10}$$

Then, on solving, (3.8) can be written as

$$\cos(k\Delta) = \cos(k_{dz}d_d)\cos(k_{pz}d_p) - \frac{1}{2}\left(\frac{\eta_p}{\eta_d} + \frac{\eta_d}{\eta_p}\left[1 + \left(\varepsilon_{21}\tan\theta_p\right)^2\right]\right)\sin(k_{dz}d_d)\sin(k_{pz}d_p) \tag{3.11}$$

$$k = \frac{1}{\Delta}\cos^{-1}\left\{\cos(k_{dz}d_d)\cos(k_{pz}d_p) - \frac{1}{2}\left(\frac{\eta_p}{\eta_d} + \frac{\eta_d}{\eta_p}\left[1 + \left(\varepsilon_{21}\tan\theta_p\right)^2\right]\right)\sin(k_{dz}d_d)\sin(k_{pz}d_p)\right\} \tag{3.12}$$

Using this matrix method, dispersion relation characteristic has been studied for different structure parameters: applied magnetic field, electronic concentration, thickness of plasma layer, angle of incidence and collision frequency and the outcomes are discussed.

3.2 Analysis of Dispersion Relation Characteristics

Dispersion relation defines the distribution of the wave into various frequencies on passing through the PPC structure. Electromagnetic wave analysis for binary PPC is presented here for different plasma parameters like plasma density, plasma width, collision frequency and other parameters like external magnetic field and angle of incidence. The results are discussed as follows:

1. The dispersion relation characteristic, as shown in Fig.3.2 is analyzed for the different magnetic field, $B_{0,}$ in 1-50GHz frequency range where other parameters are taken as: thickness $d_p = 5mm$, $d_d = 0.5mm$, refractive index n_d =2 and electronic concentration N=10^{13}cm^{-3}.The wave is considered to be incident normal to the boundary; therefore loss tangent γ =0.Here, EPF, known as the effective plasma frequency, is defined as the lowest frequency that can pass through the PPC. It is observed that EPF shifts to lower value as magnetic field is increased. The values of FPF are found as 23.11, 10.19 and 2.44GHz for B_0=0, 2T and 10T respectively. It can be observed that EPF approaches toward zero as magnetic field increases and can have zero value for a particular value of magnetic field which leads to the breakdown of the plasma property and the structure will behave much like dielectric. Here, one can also notice that effective plasma frequency is always found to be less than the bulk plasma frequency. In same, photonic bandgaps i.e. flat of the dispersion characteristic is also found shifted at lower frequencies as magnetic field is increased. The PBGs are determined by the existence of surface plasmon modes, which appear due to the coupling of dielectric and plasma at the boundary. At the plasma to dielectric boundary, change of permittivity from positive to negative value lead to flat band interface in dispersion relation.

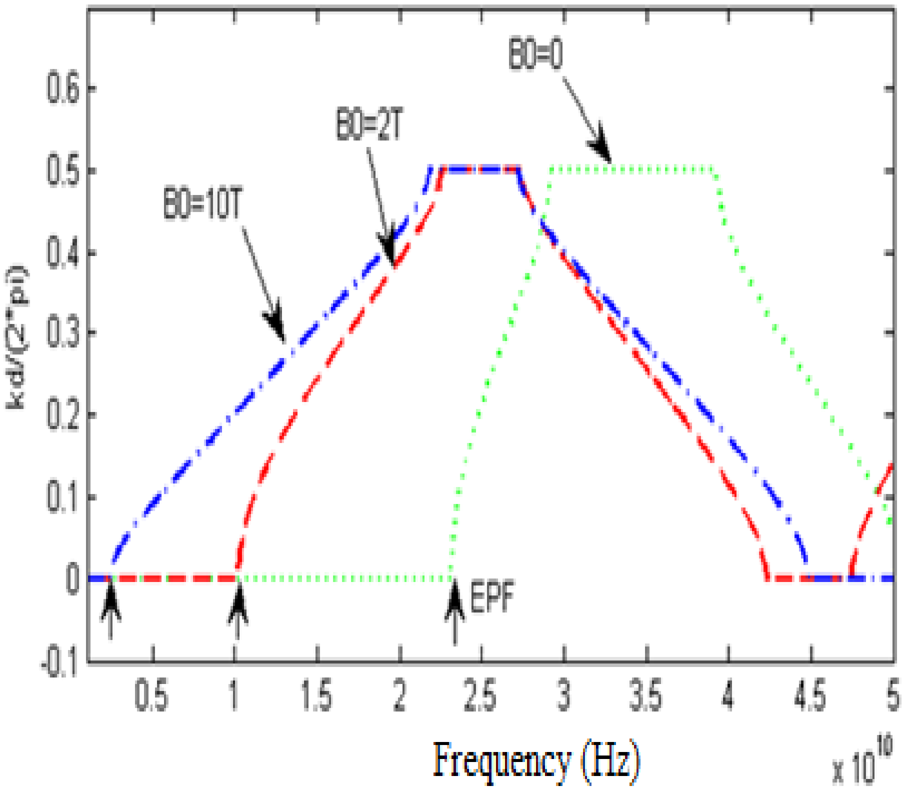

Fig. 3.2 Dispersion relation characteristic with variable static magnetic field

2. The characteristic shown in Fig.3.3 is analyzed for the different electronic concentration N, where other parameters are taken as, thickness $d_p = 5mm$, $d_d = 0.5mm$, refractive index n_d =2 and applied magnetic field B_0= 2T. From Fig.3.3, it is quite visible that the EPF is increasing as electronic concentration increases. For very small of N such as 10^{11}cm^{-3} the effective plasma frequency advances to zero thus behaving like all dielectric photonic crystal.

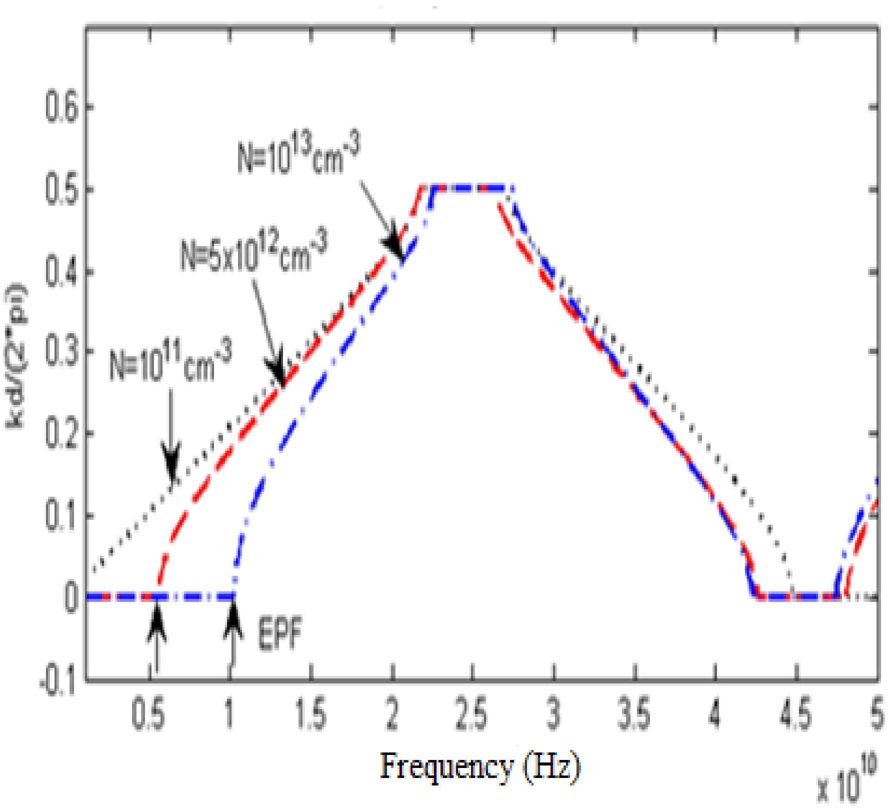

Fig. 3.3 Dispersion relation characteristic with variable electronic concentration

3. Here, dispersion characteristic as shown in Fig.3.4 is analyzed by varying the plasma thickness d_p whereas other parameters are considered as, thickness $d_d = 0.5mm$, refractive index n_d =2, electronic concentration N=10^{13}cm^{-3}and applied magnetic field B_0= 2T. It can be observed that effective plasma frequency increases with increase in the thickness.

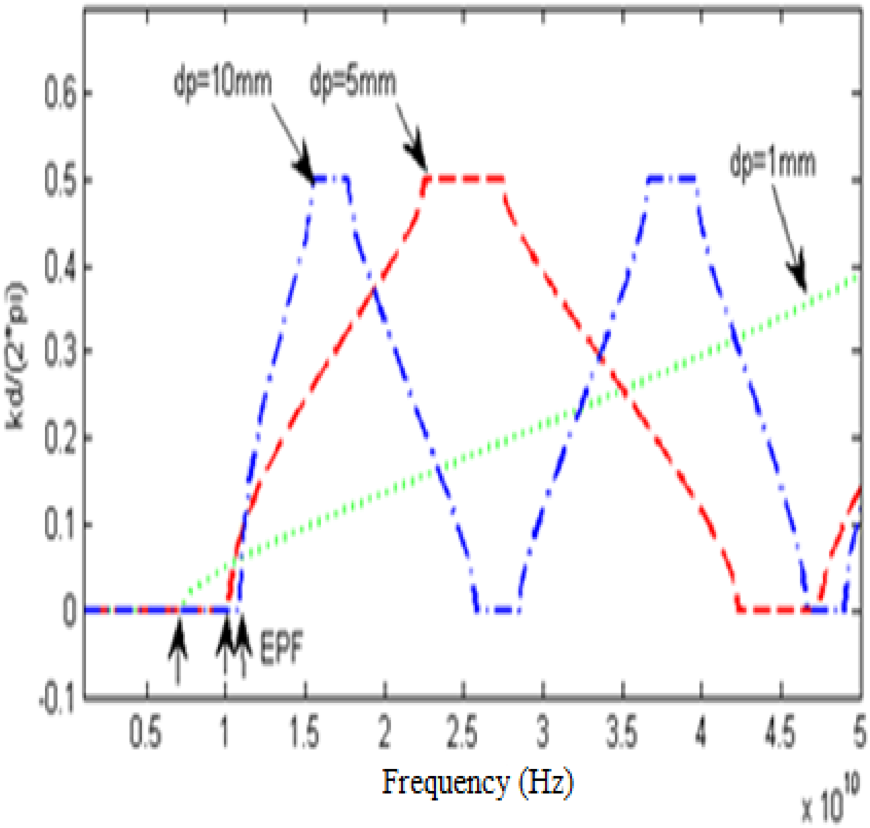

Fig. 3.4 Dispersion relation characteristic with variable thickness of plasma layer

4. The dispersion relation characteristic, as shown in Fig.3.5, is analyzed for different angle of incidence θ where other parameters are taken as: thickness $d_p = 5mm, d_d = 0.5mm$, refractive index n_d =2, electronic concentration N=10^{13}cm^{-3} and applied magnetic field B_0= 2T. From the Fig.3.5, it can be observed that in the presence of magnetic field, EPF increases as angle of incidence is increased from 0^0 to 80^0.

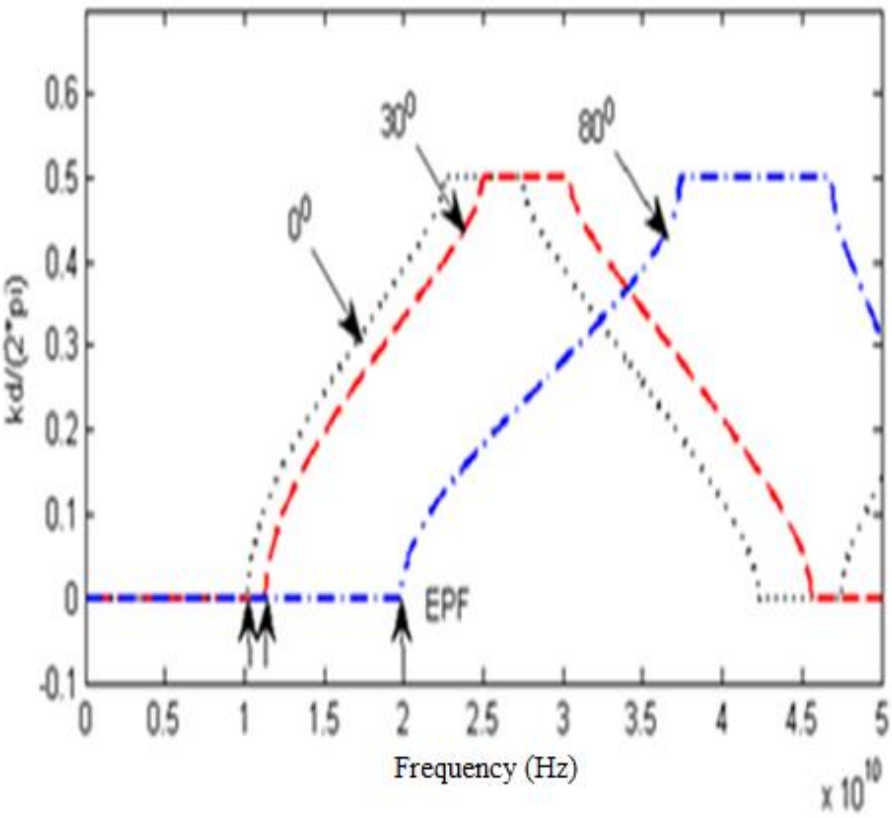

Fig. 3.5 Dispersion relation characteristic with variable angle of incidence

5. Dispersion relation characteristic as shown in Fig.3.6 is analyzed for different values of collision frequency, whereas other parameters are: thickness $d_p = 5mm$, $d_d = 0.5mm$, refractive index n_d =2, electronic concentration N=10^{13}cm^{-3} and applied magnetic field B_0= 2T. It is observed that effect of collision frequency is very insignificant, where PBG and EPF are found unaffected.

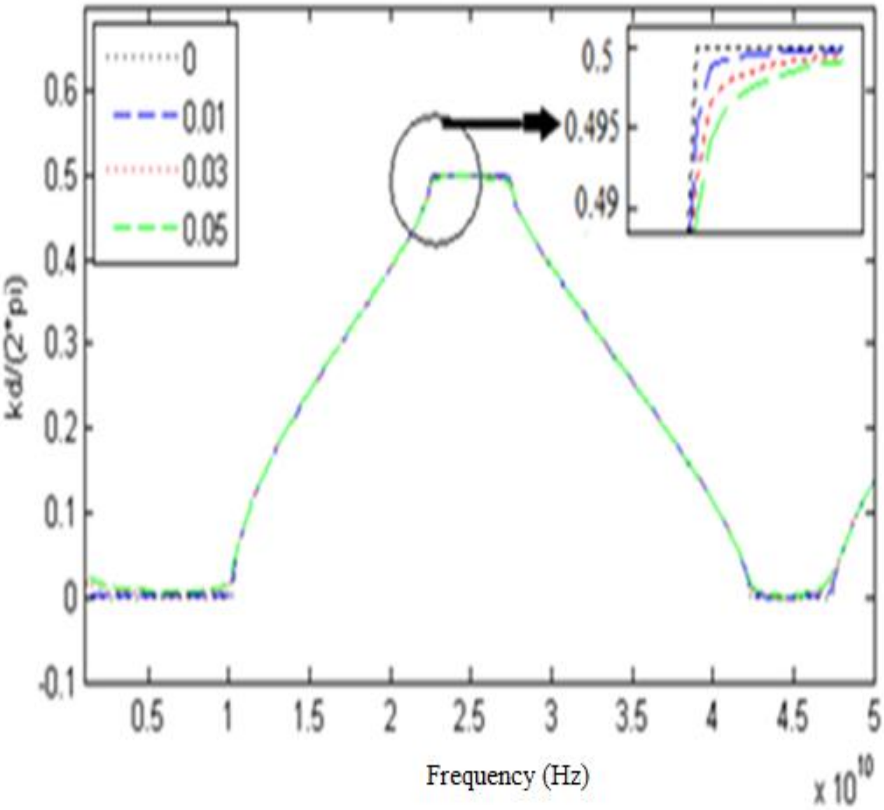

Fig. 3.6 Dispersion relation characteristic with variable collision frequency

The above observation confirms wide tunability of PPC structure for the PBGs. It mainly depends on applied magnetic field, electronic concentration, thickness of plasma layer and angle of incidence. These parameters can be changed without any structural change of PPCs. This also provides an option in PPC to switch from one PBG to another in a very fast manner by electronically varying one of the parameters.

CHAPTER 4

Analysis of Ternary PPC using 1-D Mathematical Modeling

4.1 Introduction

This chapter describes the comparison of binary PPC and ternary PPC when excited by the electromagnetic TM-polarized wave. We have already studied the dispersion relation characteristics for binary PPC and observed that the photonic bandgaps can be effectively altered by varying the structure parameters without any physical change in the structure. The change in extrinsic and intrinsic parameters like electronic concentration, static magnetic field and thickness of plasma layer, etc. helped in obtaining a better tunability of the PPC structure. The same analysis has been extended for ternary PPC, with periodicity of layers (ABC), as shown in Fig.4.1 wherein, A is glass, B is plasma and C is MgF_2.

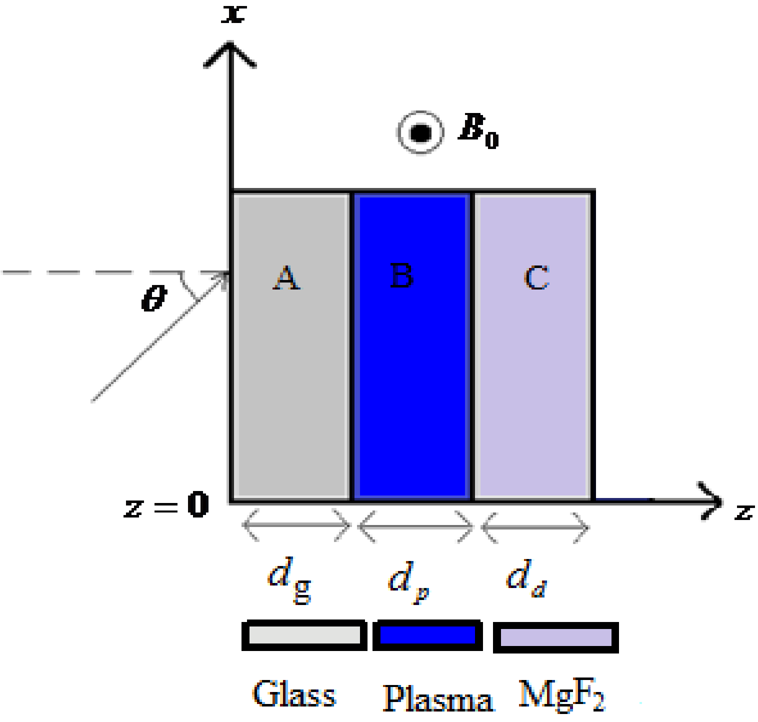

Fig. 4.1 Schematic of 1-D model of magnetized ternary-PPC

The study here shows that the additional dielectric layer in the ternary PPC provides shifting of EPF at lower side in frequency band and this becomes more significant when number of periodic ternary layers is increased. The results have been compared and found to be in good agreement with theory. This has been verified using graphical analysis in MATLAB.

4.1.1 Mathematical Modeling

For the analysis of characteristics, a magnetized ternary-PPC is considered with periodicity of layers (ABC), as shown in Fig.4.1 where, A is glass, B is plasma and C is MgF_2. The layers A, B and C have thickness d_g, d_p and d_d and refractive indices n_g, n_p and n_d, respectively. The structure is spatially periodic about the lattice constant ($\Delta = d_g + d_p + d_d$) and excited by a TM polarized wave which is incident at an angle θ on the left plane boundary at z=0.

As discussed in chapter 3, the TM-wave satisfies Helmholtz equation; with its general solution in the ternary PPC given by:

$$H(z) = \begin{cases} a_m e^{ik_{gz}z} + b_m e^{-ik_{gz}z}, m\Delta < z < m\Delta + d_g \end{cases} \tag{4.1a}$$

$$\begin{cases} c_m e^{ik_{pz}z} + d_m e^{-ik_{pz}z}, m\Delta + d_g < z < m\Delta + d_p \end{cases} \tag{4.1b}$$

$$\begin{cases} e_m e^{ik_{dz}z} + f_m e^{-ik_{dz}z}, m\Delta + d_p < z < (m+1)\Delta \end{cases} \tag{4.1c}$$

where, $m = 0$, ± 1, ± 2 ...so on and b_m, d_m, f_m and a_m, c_m, e_m are the wave amplitudes in the forward and the backward direction, respectively; k_{gz}, k_{pz} and k_{dz} are the normal components of the wave number given by [8]:

$$k_{gz} = \sqrt{k_0^2 n_g^2 - \beta^2} = k_0 n_g \cos(\theta_g) = \omega/_c \sqrt{\varepsilon_g} \cos(\theta_g) \tag{4.2a}$$

$$k_{pz} = \sqrt{k_0^2 n_p^2 - \beta^2} = k_0 n_p \cos(\theta_p) = \omega/_c \sqrt{\varepsilon_p} \cos(\theta_p) \tag{4.2b}$$

$$k_{dz} = \sqrt{k_0^2 n_d^2 - \beta^2} = k_0 n_d \cos(\theta_d) = \omega/_c \sqrt{\varepsilon_d} \cos(\theta_d) \tag{4.2c}$$

Here, θ_g, θ_p and θ_d are the angle of incidence of the wave in the glass, plasma and MgF$_2$, respectively.

Now, the dispersion relation can be determined by the half trace of matrix M i.e. equivalent of transmission matrix which is obtained from multiplication of transfer matrices of all the three layers given by

$$M = M_g M_p M_d = \begin{bmatrix} A & B \\ C & D \end{bmatrix}, \tag{4.3}$$

and dispersion relation is given by

$$\cos(k\Delta) = \frac{1}{2}(A + D) \tag{4.4}$$

where, M_g, M_p, M_d are respective individual transmission matrix of the three different layers and k is the Bloch wave vector used to describe the conduction of an electron inside the PPC structure. Based on mathematical analysis, dispersion relation for ternary PPC is be obtained as [25]

$$\cos(k\Delta) = \cos(k_{gz}d_g)\cos(k_{pz}d_p)\cos(k_{dz}d_d) - \frac{1}{2}\left(\frac{\eta_p}{\eta_g} + \frac{\eta_g}{\eta_p}\right)\sin(k_{gz}d_g)\sin(k_{pz}d_p)\cos(k_{dz}d_d)$$
$$-\frac{1}{2}\left(\frac{\eta_p}{\eta_d} + \frac{\eta_d}{\eta_p}\right)\cos(k_{gz}d_g)\sin(k_{pz}d_p)\sin(k_{dz}d_d) - \frac{1}{2}\left(\frac{\eta_d}{\eta_g} + \frac{\eta_g}{\eta_d}\right)\sin(k_{gz}d_g)\cos(k_{pz}d_p)\sin(k_{dz}d_d) \tag{4.5}$$

where, η_g, η_p, η_d are wave impedances in region A, B and C respectively, which are expressed as

$$\eta_p = \sqrt{\varepsilon_{TM}}\left(\sqrt{\varepsilon_0/\mu_0}\right)\left(1/\cos\theta_p\right),$$

$$\eta_r = \sqrt{\varepsilon_r}\left(\sqrt{\varepsilon_0/\mu_0}\right)\left(1/\cos\theta_r\right), r = g, d$$

Now, dispersion relation characteristic has been studied for different extrinsic and intrinsic parameters, such as electronic concentration, static magnetic field, thickness of plasma layer and results have been presented for binary and ternary-PPC in comparative manner.

4.2 Comparison of Dispersion Relation Characteristics between Binary PPC and Ternary PPC

Here, comparative study of the binary and ternary plasma photonic band structure is presented where dispersion relation is analyzed for variable magnetic field, electronic concentrations and thickness of plasma. The wave is considered to be incident normal to the boundary with loss tangent γ =0. The results are obtained as follows:

1. Dispersion relation characteristics for different values of magnetic field B_0=2T and B_0=6T is shown in Fig.4.2 (a) and (b), for both binary and ternary PPC. Here other parameters are taken as, N=$10^{13}$$cm^{-3}$, n_g=1.5, n_d=1.38; thickness $d_p = 5mm$, $d_g = 0.5mm$ and $d_d = 0.5mm$. Result shows that effective plasma frequency (EPF) is a decreasing function of magnetic field and approaches to zero as magnetic field is increased. This leads to the breakdown of plasma property. EPF in binary is found higher as compared to ternary PPC and that values are given as 10.5GHz and 9.9GHz at B_0=2T, respectively. As magnetic field increases to B_0=6T, EPF is observed to be shifted to the lower values i.e. 4.1GHz and 3.8GHz. In same, comparative shift in binary is found more as compared to the ternary. The reduction of EPF in ternary PPC causes the structure to behave like a dielectric and has more dielectric properties compared to the binary PPC.

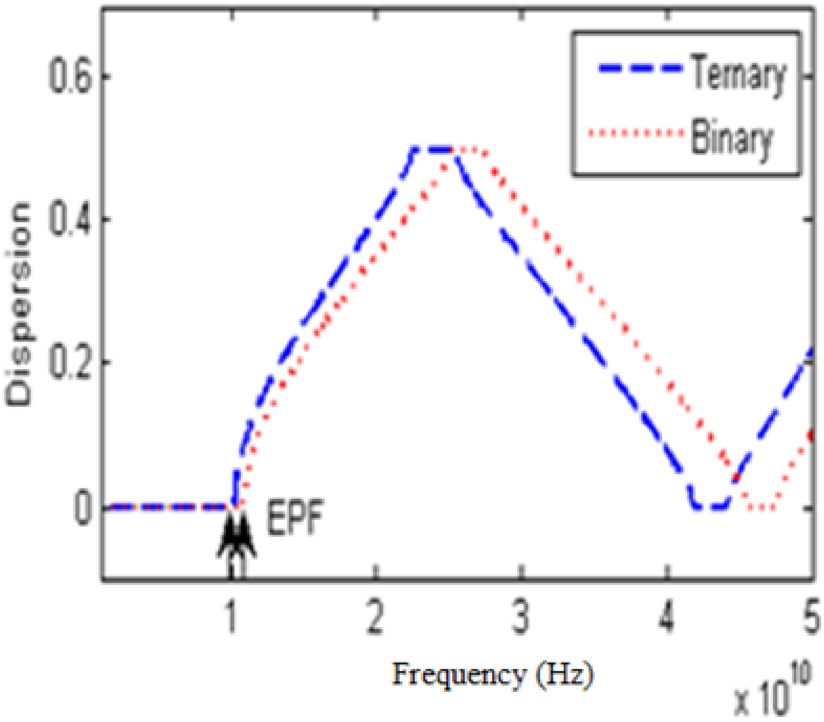

Fig. 4.2(a) Dispersion relation characteristic for static magnetic field B_0=2T

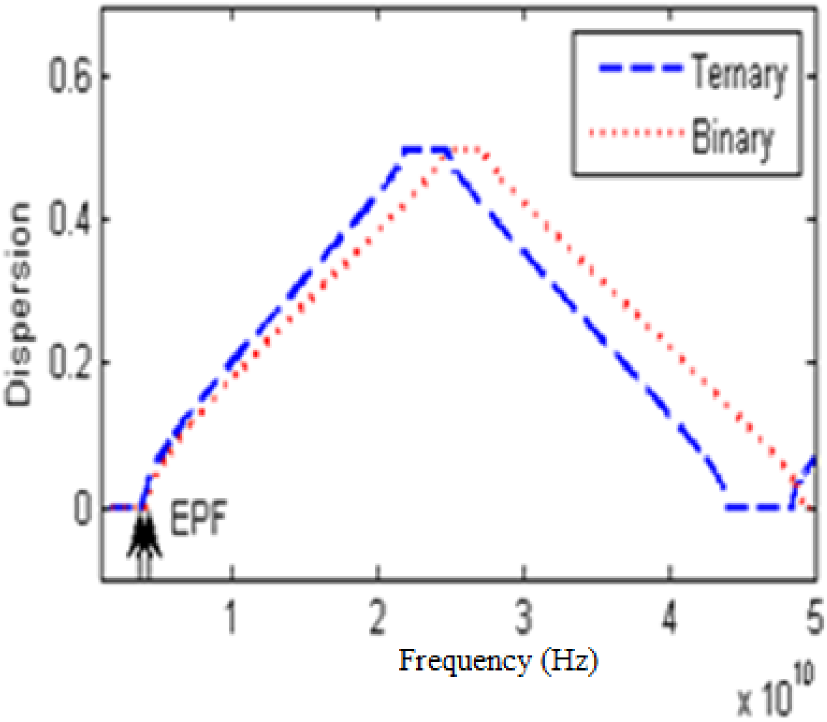

Fig. 4.2(b) Dispersion relation characteristic for static magnetic field B_0=6T

2. In Fig.4.3 (a) and (b), characteristic of PPC is studied for the two different values of electronic concentration i.e. N= 10^9cm^{-3} and 10^{13}cm^{-3} where other parameters are taken as $d_p = 5mm$, $d_g = 0.5mm$, $d_d = 0.5mm$; refractive index n_g =1.5, n_d =1.38 and applied magnetic field B_0= 2T. It is observed that EPF increases with increase in electronic concentration. In same, EPF is found lower in ternary PPC as compared to the binary PPC.

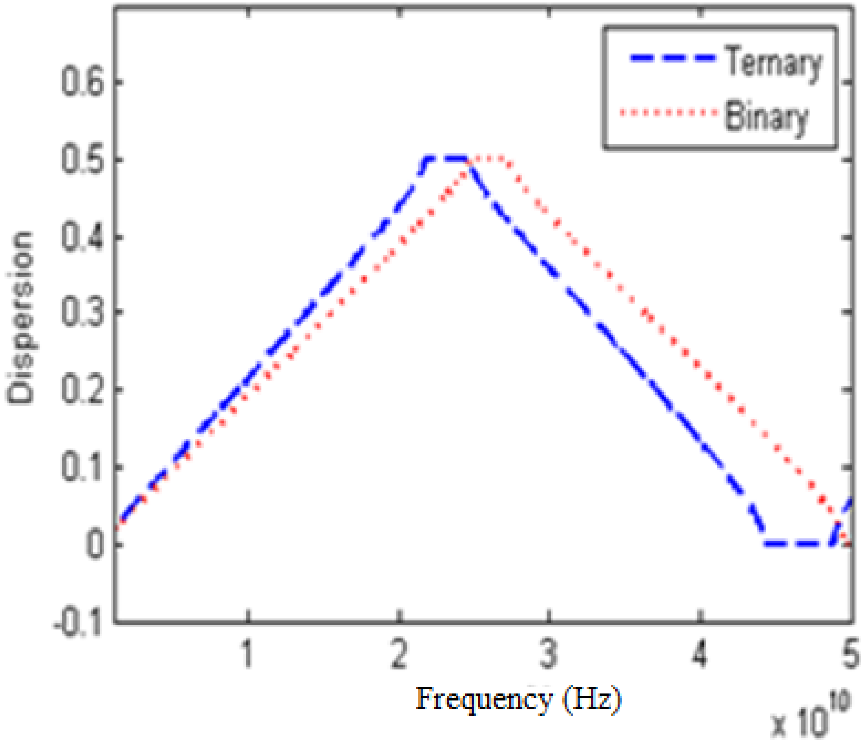

Fig. 4.3(a) Dispersion relation characteristic for electronic concentration N= 10^9cm^{-3}

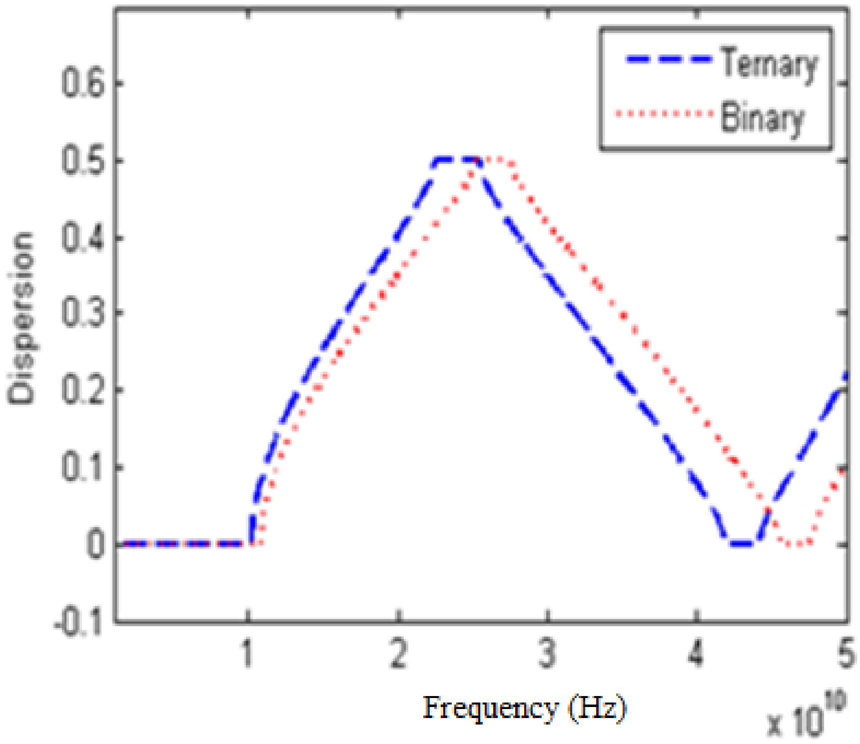

Fig. 4.3(b) Dispersion relation characteristic for electronic concentration N= 10^{13}cm^{-3}

3. In Fig.4.4 (a) and (b), PPC characteristic is analyzed for $d_p = 5mm$ and $d_p = 10mm$; whereas other parameters are considered as, thickness $d_g = 0.5mm$, $d_d = 0.5mm$; refractive index n_g=1.5, n_d=1.38; N=10^{13}cm^{-3} and B_0= 2T. It can be observed that effective plasma frequency increases with increase in the thickness. Also, there is decrease in EPF for ternary PPC compared to the binary one. This causes the structure to have more dielectric like behavior.

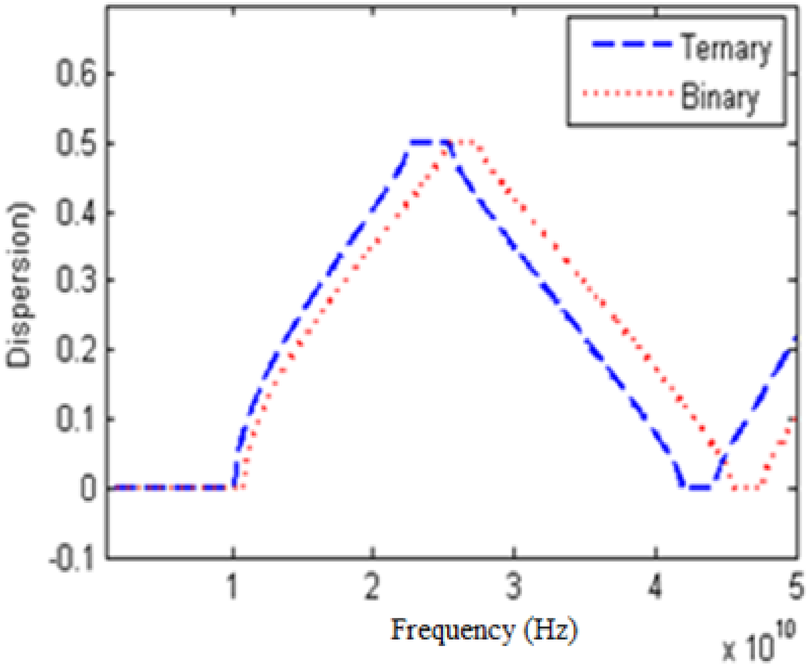

Fig. 4.4(a) Dispersion relation characteristic for plasma width $d_p = 5mm$

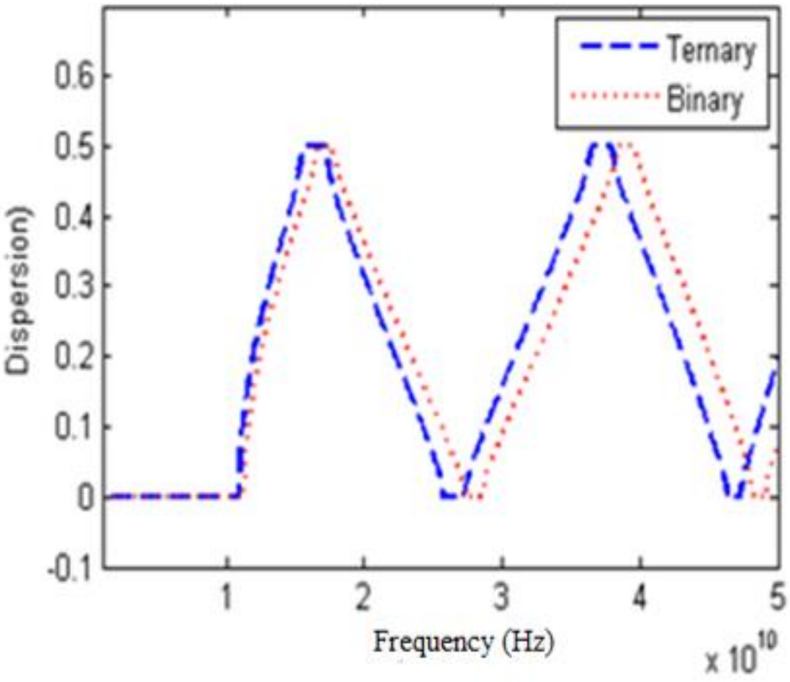

Fig. 4.4(b) Dispersion relation characteristic for plasma width $d_p = 10mm$

The above observation validates that the propagation of wave in PPC depends on parameters like applied magnetic field, electronic concentration and thickness of plasma layer which can be varied without changing the structure of PPC. This property enables the wide tunability of PPCs. In comparative study of binary and ternary PPC, it is found that EPF is shifted to the lower side of the band when one more layer is added in binary to get the ternary PPC. This could be more significant as more number of periodic layers is attached.

CHAPTER 5

Analysis of Trapped Oscillation in Binary PPC

5.1 Introduction

In previous section, dispersion relation characteristic is investigated in the range of 1-50GHz for both binary and ternary PPC structures. The study in this chapter is extended to the higher frequency range up to 140GHz for binary PPC, given in Fig.3.1, where bandgap characteristic of PPCs is found periodic with frequency. In certain frequency range, performance is observed to be very unpredictable or non-linear. This discontinuity is comprehensively investigated and found associated to the extra-ordinary mode (X-mode) present in magnetized plasma. The wave propagation in the extra-ordinary mode depends on the hybrid plasma frequency (f_h) along with bulk plasma frequency (f_p) i.e. given by [41],

$$f_h = \left(\sqrt{f_p^2 + \frac{1}{4} f_c^2} \right) + \frac{1}{2} f_c \qquad (5.1)$$

It is defined as the right-circularly polarized cut-off frequency. This hybrid frequency is clearly a function of plasma frequency and cyclotron frequency which are further dependent on structural parameters like electronic concentration and applied magnetic field. The wave propagating near to this hybrid frequency produces trapped oscillation and leads to discontinuity in PBGs. The non-linearity in dispersion relation and transmittance characteristics can be observed for this right-circled cut off frequency in results. This is found to be associated with extra-ordinary modes in magnetized plasma which leads to trapped oscillations. The trapped oscillations are only found when the frequency of the wave is greater than the plasma frequency as well as it must lie between the plasma frequency and the hybrid cut off frequency. It can be also observed that the discontinuity is not found when the applied magnetic field is zero. However, when static magnetic field is applied, discontinuity appears and shifts to higher frequency with increase in magnetic field. This confirms that the problem is associated to extra-ordinary modes, present in magnetized plasma only when right-circularly polarized cut-off frequency is considered. At left-circled cut off frequency, wave frequency is found below the plasma frequency. Therefore, non-linearity and resonance are not observed. The left-circled wave has a stop band at low frequencies and thus, it behaves like the ordinary wave [42].

5.2 Analysis of Dispersion Relation Characteristics

1. Analysis of bandgap is extended up to 140GHz and shown in Fig.5.1 (a), (b) and (c), where parameter are considered as thickness $d_p = 5mm$, $d_d = 0.5mm$, refractive index n_d =2 and electronic concentration N=$10^{13}$$cm^{-3}$. The above discontinuity is found to be in the range of 61-68GHz when applied magnetic field is B_0=2T and it is shifted to the 112-119GHz when applied magnetic field is taken as B_0=4T. In same, hybrid frequency is calculated as 67.83GHz and 118.72 GHz for B_0=2T and B_0=4T respectively. It can be observed that discontinuity in PBG appears near to hybrid plasma frequency and it is disappeared when no magnetic field is applied. This confirms that this is associated to the extra-ordinary mode present in magnetized plasma.

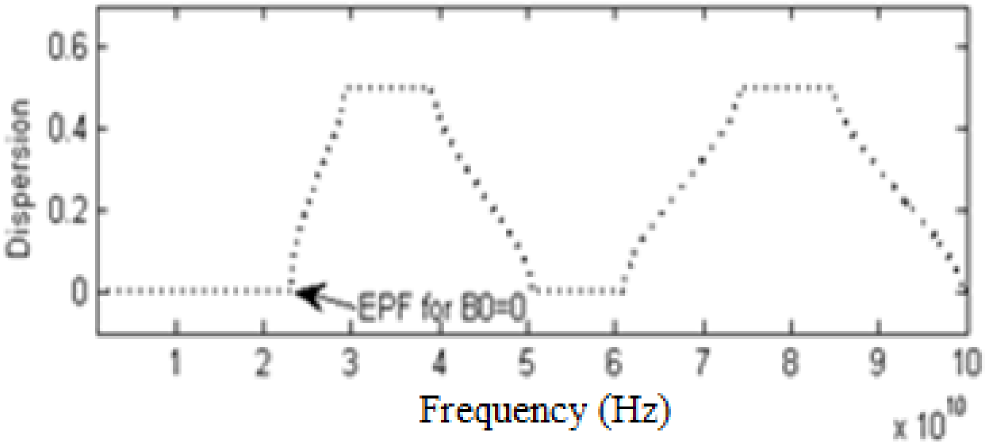

Fig. 5.1(a) Dispersion relation characteristic for static magnetic field B_0=0

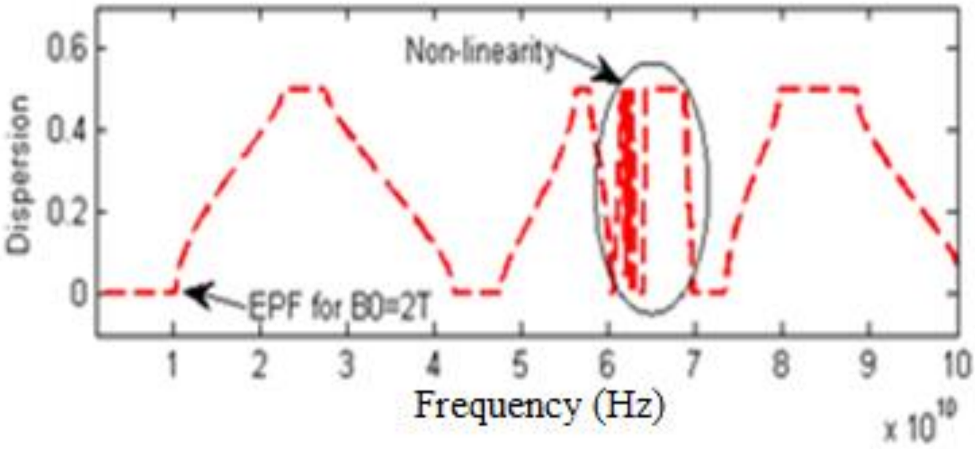

Fig. 5.1(b) Dispersion relation characteristic for static magnetic field B_0=2T

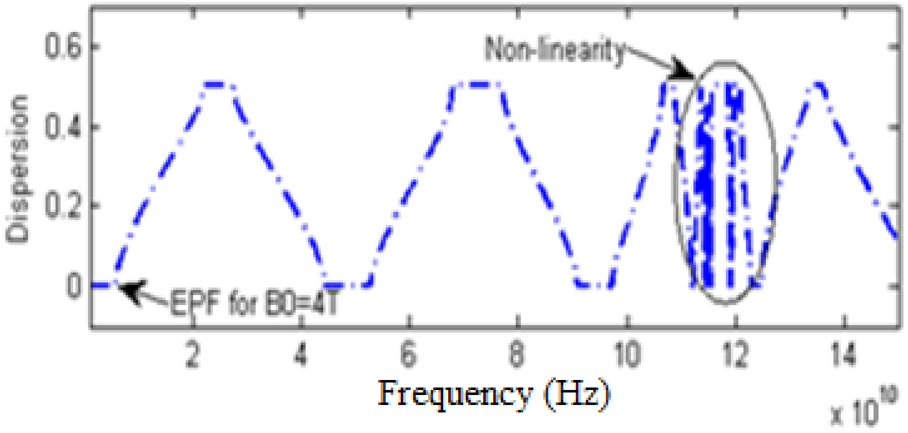

Fig. 5.1(c) Dispersion relation characteristic for static magnetic field B_0=4T

2. The similar analysis has been performed by having fixed magnetic field value, B0=2T and varying the electronic concentration in order of $N=10^9 cm^{-3}$, $10^{11} cm^{-3}$ and $10^{13} cm^{-3}$. The outcomes are shown in Fig.5.2 (a), (b) and (c), and it is found that the observed oscillation is reduced as electronic concentration reduces and becomes almost negligible for values below $N=10^9 cm^{-3}$. It means above discontinuity can be compensated by decreasing the electronic concentration. However, there is always a constraint to this since reducing the electronic concentration beyond a certain limit makes the structure behave more like dielectric material due to break down of the plasma behavior.

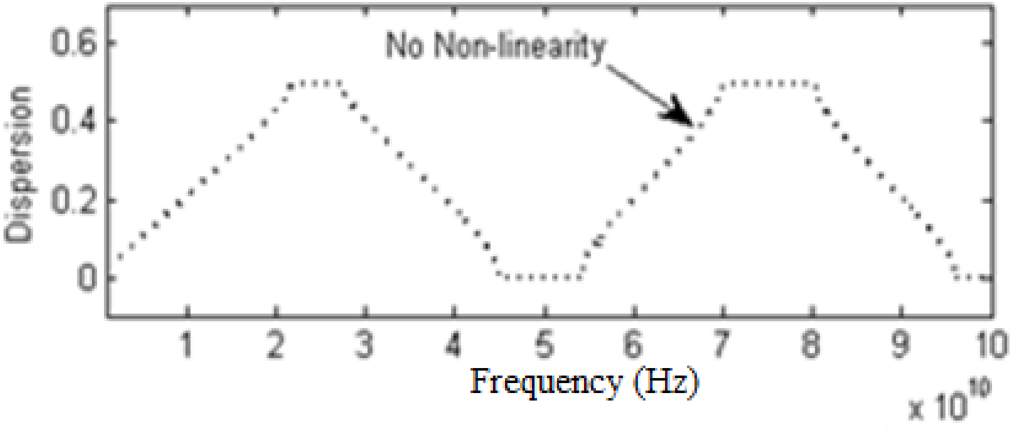

Fig. 5.2(a) Dispersion relation characteristic for electronic concentration $N= 10^9 cm^{-3}$

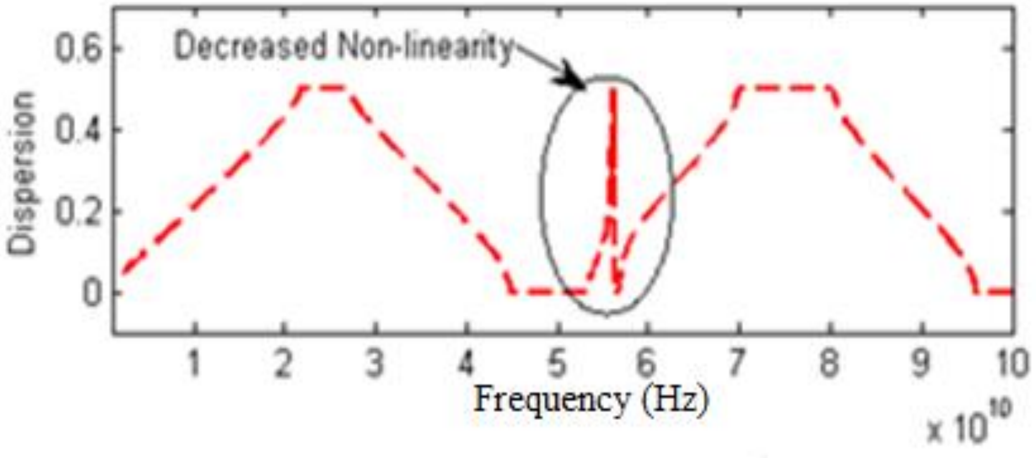

Fig. 5.2(b) Dispersion relation characteristic for electronic concentration N= 10^{11}cm^{-3}

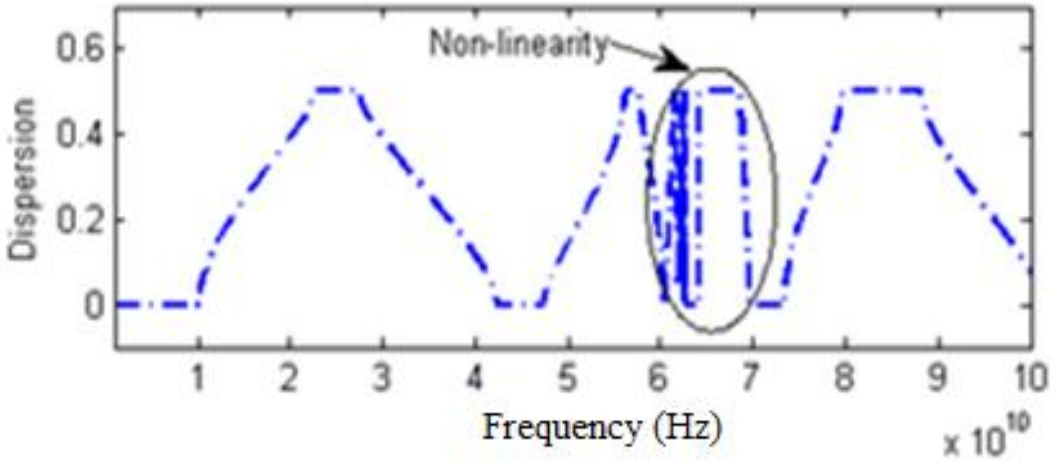

Fig. 5.2(c) Dispersion relation characteristic for electronic concentration N= 10^{13}c m^{-3}

5.3 Analysis of Transmittance Characteristics

Here, transmittance is characterized for different values of magnetic field and electronic concentration. The observation below validates that the propagation of wave in PPC depends on parameters like applied magnetic field and electronic concentration and thus, allows tunability of the structure by varying these parameters. There is presence of trapped oscillations in the structure which causes non-linearity in the characteristics because of the presence of external magnetic field and when electronic concentration is increased beyond a certain level.

5.3.1 Mathematical Modeling

As discussed in chapter 3**,** wave transmission through lattice given in Fig.3.1 can be written as,

$$\begin{bmatrix} a_{m-1} \\ b_{m-1} \end{bmatrix} = M \begin{bmatrix} a_m \\ b_m \end{bmatrix} \tag{5.2}$$

where, b_{m-1} and a_{m-1} are forward and reflected wave amplitude at left boundary of the lattice and b_m and a_m are forward and reflected wave amplitude of the transmitted wave and M is known as the transmission matrix. It is given by the multiplication of transfer matrices of the two cascaded layers of plasma and dielectric and evaluated in terms of the ABCD parameters as:

$$M = M_d M_p = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{5.3}$$

Using (5.3), the transmission coefficient (t) is expressed as:

$$t = \frac{2\eta_0}{A\eta_0 + B\eta_0\eta_s + C + D\eta_s}, \tag{5.4}$$

which gives Transmittance,

$$T = \frac{n_s \cos\theta_s}{n_0 \cos\theta} |t|^2 \tag{5.5}$$

where, η_0 and η_s are wave impedances and n_0 and n_s are refractive indices of air and substrate, respectively.

These are given by $\eta_0 = \left(\sqrt{\varepsilon_0 / \mu_0}\right)\left(1/\cos\theta\right)$ and $\eta_s = \left(\sqrt{\varepsilon_0 / \mu_0}\right)\left(1/\cos\theta_s\right)$.

Also, the refractive indices are related by Snell's law of refraction, $n_0 \sin\theta = n_s \sin\theta_s$

Here, the substrate is taken as air. Therefore, $\eta_s = \eta_0$.

5.3.2 Characteristic curves

1. Now, transmittance has been plotted, for different values of magnetic field B_0 and other structural parameters as: thickness $d_p = 5mm$ and $d_d = 0.5mm$, refractive index n_d =2 and electronic concentration N=10^{13}cm^{-3}. The transmission curves in Fig.5.3 (a), (b) and (c), verify the fact that the presence of magnetic field leads to trapped oscillations in the structure, thus causing discontinuity in the characteristics. It is found that there is no discontinuity present when no magnetic field is applied. However, when magnetic field is applied equal to B_0=2T and B_0=4T, there is discontinuity in the characteristics in the range of 61-68GHz and 112-119GHz, respectively, as shown by the encircled region in the figure below. It is seen that the discontinuity shifts to higher frequency when applied magnetic field is increased.

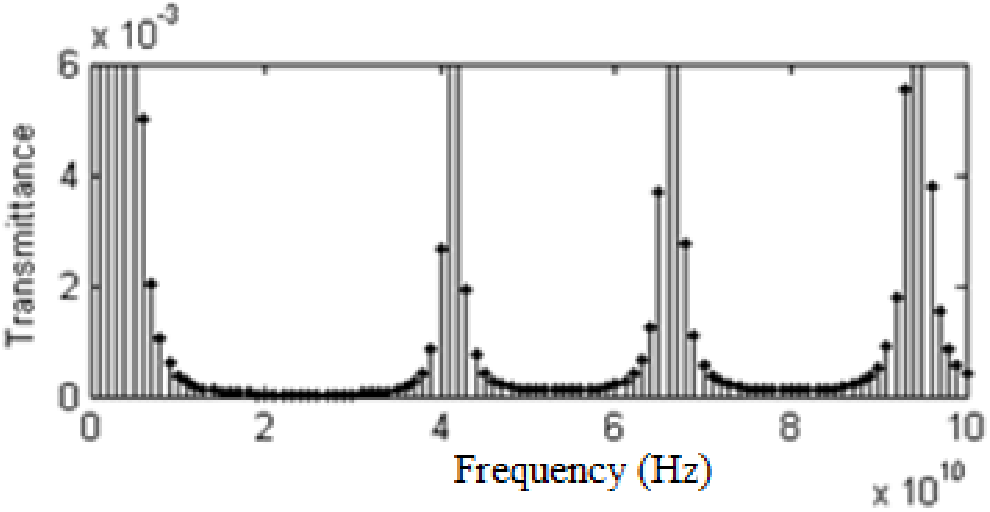

Fig. 5.3(a) Transmittance characteristic for static magnetic field B_0=0

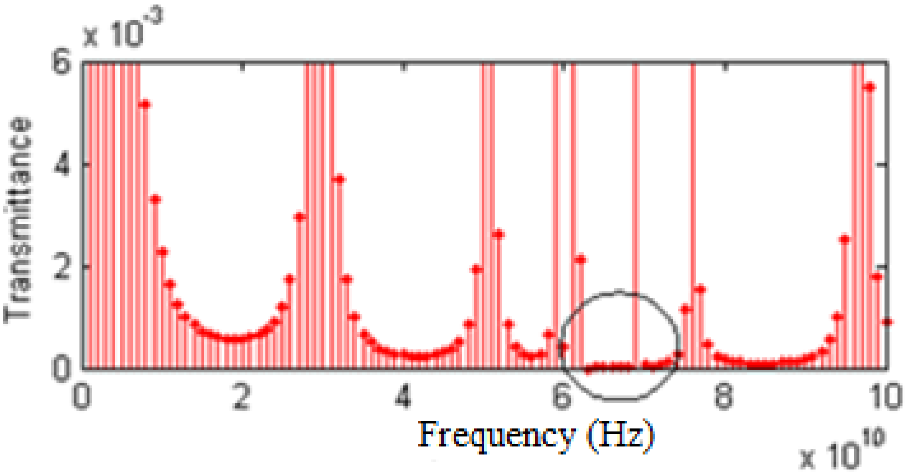

Fig. 5.3(b) Transmittance characteristic for static magnetic field B_0=2T

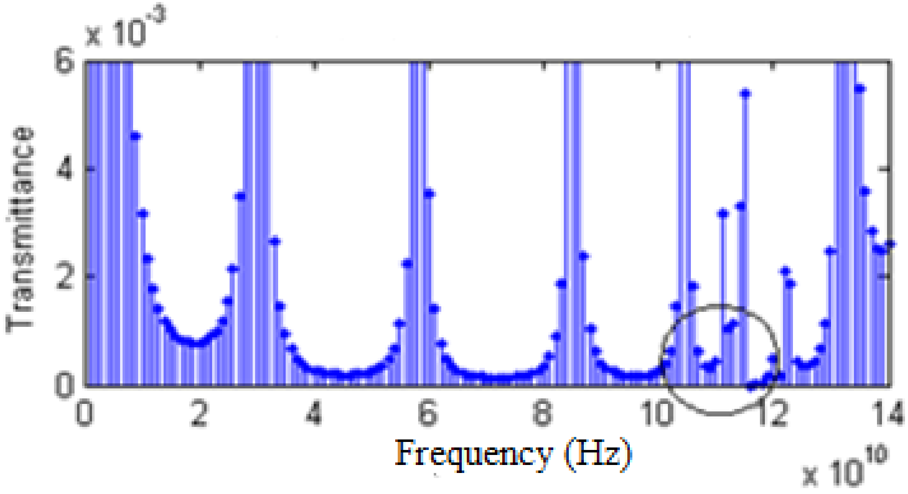

Fig. 5.3(c) Transmittance characteristic for static magnetic field B_0=4T

2. Transmittance is shown here for different values of electronic concentration N, where other parameters are considered as thickness $d_p = 5mm$, $d_d = 0.5mm$, refractive index n_d =2 and applied magnetic field B_0=2T. It is found that the trapped oscillations shifts to lower frequency when the electronic concentration is decreased and becomes almost negligible for the values below N=10^9cm^{-3} and hence, the result is in similarity to the dispersion relation characteristics.

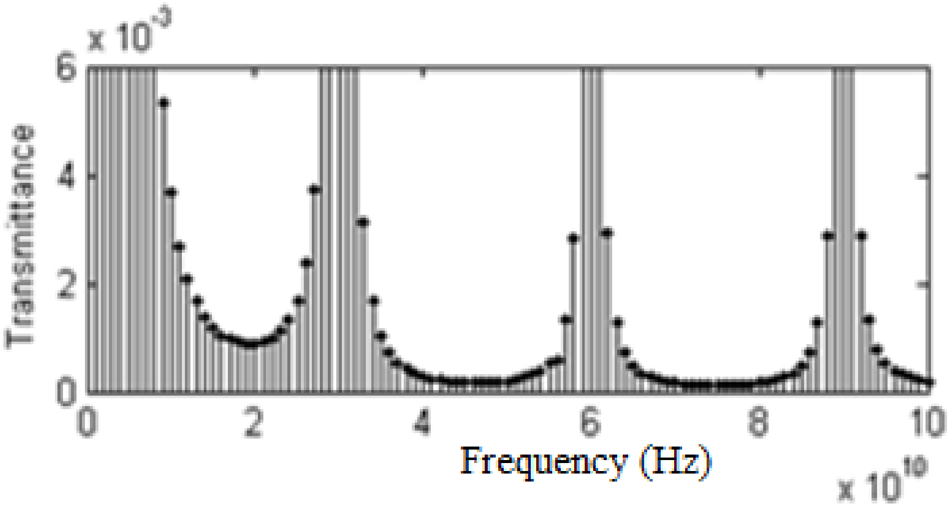

Fig. 5.4(a) Transmittance characteristic for electronic concentration N= 10^9cm^{-3}

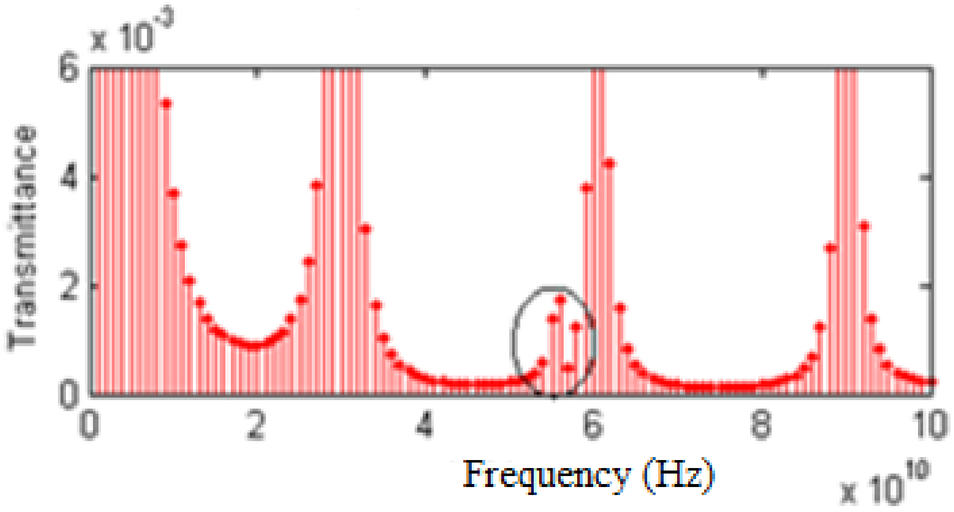

Fig. 5.4(b) Transmittance characteristic for electronic concentration N= 10^{11}cm^{-3}

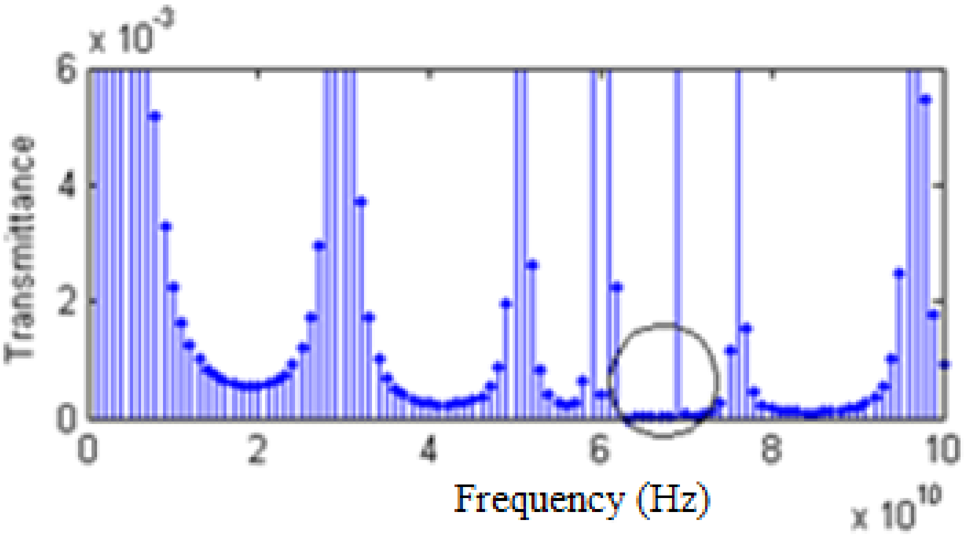

Fig. 5.4(c) Transmittance characteristic for electronic concentration N= 10^{13}cm^{-3}

The transmittance curves for the same structure confirm the correctness of the dispersion curves and verify the fact that trapped oscillations occur in specific frequency regions, when external magnetic field is applied and for high electronic concentration.

CHAPTER 6

Concluding Remarks and Future Scope

6.1 Conclusion

The dissertation gives the detailed wave analysis of magnetized PPC structure using 1-D mathematical modeling. Various characteristics for binary and ternary-PPC structures have been investigated for different structure parameters such as: applied magnetic field, electronic concentration, plasma width, angle of incidence and collision frequency. Analysis shows that the propagation of wave in PPC mainly depends on these parameters. . The study has been done in various steps that are given as follows:

1. Initially, structure of binary-PPC has been studied and analyzed using mathematical modeling in MATLAB software. The analysis shows that wave propagation in the given structure depends on the extrinsic and intrinsic parameters. The dispersion relation characteristic of PPC shows that the effective plasma frequency (EPF) and photonic bandgaps (PBGs) can be varied with these parameters that enable to tune it electronically for desired PBGs in very fast manner.
2. The tunability of EPF for ternary PPCs has been investigated for different plasma parameters and presented in comparative manner with binary PPC. The value of EPF is found to be lower for ternary PPC as compared to the binary one and this difference could be more significant when more number of periodic layers is structured.
3. Finally, the analysis has been extended to higher frequency range upto 140GHz. On extending the analysis, a discontinuity in dispersion relation characteristic has been observed. The problem is investigated and found associated to the extra-ordinary mode (X-mode) present in magnetized plasma that leads to trapped oscillation near hybrid frequency of the plasma. This discontinuity can be shifted in a desired frequency range by having the suitable value of magnetic field and electronic charge concentration.

The photonic band structures can be effectively adjusted to obtain the useful characteristics such as: highly tunable dispersion, to slow down light waves in controllable manner, operation at wide wavelength range and optical functions such as switching. This property can be utilized for the design of filters in the range of UHF, SHF and EHF band.

6.2 FUTURE SCOPE

The presented work is based on the analysis and simulation of magnetized binary PPC using 1-D mathematical modeling, where trapped oscillation in PBG has been highlighted. This work can be further extended for two-dimensional and three-dimensional analysis, which could provide better simulation representation. It can also be extended for multiple layers of plasma and dielectric in PPC for broad band applications. The photonic band gap in PPC can be effectively tailored by manipulating its structure characteristics and this property can be used in designing of frequency filters and selectors in millimeter range. The PBG can be shifted to any prescribed frequency band by having suitable parameters and thus, can help in military applications: for secured communication and imaging.

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LIST OF PUBLICATIONS

S. NO.	TITLE	PUBLICATION	STATUS
1	Analysis of 1-D Magnetized Plasma Photonic Crystal Band Gap Characteristic for Variable Plasma Parameters	PIERS CONFERENCE, AUGUST, 2016 SHANGHAI, CHINA	ACCEPTED
2	Analysis of Trapped Oscillation Modes in Magnetized PPC and its Tunability for Variable Plasma Parameters	OPTICS COMMUNICATIONS, ELSEVIER	UNDER REVIEW

THESIS

ORIGINALITY REPORT

6%	0%	5%	0%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Wu, C., T. King, W. Kuo, T. Yang, and T. Bian. "Magnetic Field Dependence of Effective Plasma Frequency for a Plasma Photonic Crystal", IEEE Photonics Journal, 2013. Publication	2%
2	Prasad, Surendra, Vivek Singh, and A. K. Singh. "The Dispersion Characteristics of a One Dimensional Plasma Photonic Crystal Having Inhomogeneous Plasma Density Profiles", Optics and Photonics Journal, 2012. Publication	<1%
3	Kumar, Rajneesh. "Plasma Photonic Crystal", Photonic Crystals - Innovative Systems Lasers and Waveguides, 2012. Publication	<1%
4	Zhang, Hai-Feng, Shao-Bin Liu, and Xiang-Kun Kong. "Enlarged omnidirectional band gap in one-dimensional plasma photonic crystals with ternary Thue–Morse aperiodic structure", Physica B Condensed Matter, 2013. Publication	<1%