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Tunable Photonic Band Gaps in One-Dimensional Magnetized Cold Plasma Photonic Crystals Using the Transfer Matrix Method

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Abstract

Plasma represents the fourth fundamental state of matter, characterized by the collective interaction of free electrons, ions and neutral particles under long-range Coulomb forces. Unlike conventional thermodynamic phase transitions, the transformation from gas to plasma occurs gradually through ionization at high temperatures or under electromagnetic excitation. In this work, the optical behavior of a one-dimensional periodic structure composed of alternating layers of air and magnetized cold plasma (MCP) is theoretically investigated. The dielectric response of the plasma medium is derived using Maxwell's equations, incorporating the effects of plasma frequency, cyclotron frequency, electron density, collision frequency and externally applied magnetic field. The refractive index of the plasma layer is obtained from its frequency-dependent permittivity and the photonic band structure and transmittance characteristics are analyzed using the Transfer Matrix Method (TMM). The results reveal that both right-hand and left-hand polarizations exhibit tunable photonic band gaps in the microwave and GHz frequency ranges. It is observed that the external magnetic field and plasma density play dominant roles in shifting band edges and controlling transmission windows, while the effective collision frequency has a comparatively weak influence. The proposed plasma photonic crystal demonstrates reconfigurable broadband reflection and narrow-band filtering behavior, highlighting its potential application in tunable microwave and terahertz photonic devices.

Keywords: Plasma; Magnetized cold plasma; Photonic crystal; Plasma photonic crystal; Photonic band gap; Transfer matrix method; Plasma frequency; Cyclotron frequency; Tunable filter; Microwave propagation

Introduction:

In terms of general physics, we are familiar with the three fundamental states of matter, which are solid, liquid and gas. Through the transfer of energy, any one of these states can be changed into another one of these states. Water (H_2O) is a noteworthy example that can be found in all three forms, which can be found in our day-to-day lives. It can be found in the form of ice (solid), water (liquid) and steam (gas). The solid phase can obviously be converted into the liquid phase and the liquid phase can be converted into the gaseous phase by injecting energy into the matter. The opposite process of the water (H_2O) may be accomplished by injecting energy into the matter and then extracting energy from the matter. There are just a few instances in which it is feasible to immediately transform a solid phase into a gaseous phase. Some

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examples of these scenarios are NH_4Cl and camphor. When an additional quantity of energy is applied to the gaseous phase of matter, the molecules that make up the gaseous phase break apart into their component atoms. Following the loss of their electrons, which results in the production of positively charged ions and the discovery of electrons with a negative charge. The ionisation potential of an atom is the minimum amount of energy required to remove one electron from the atom. This energy may have been given in the form of heat or radiation. Ionisation of charge owing to heat energy happens at high temperatures on the order of million Kelvin, which is a state that can be created in the laboratory. Ionisation occurs when charge is separated from electrons. Plasma is the ionised state of matter that simultaneously consists of charged particles and neutral particles. In this condition, matter is said to be ionised.

Plasma

As a result of the strong columbic force, plasma is made up of many different types of macroscopically neutral particles, such as a large number of interacting free electrons and ionised atoms or molecules. Certain conditions must be met before you can watch how plasma behaves in a system where charged and neutral particles interact. The Greek phrase for "something moulded" is whence we get our English word "plasma." Electrical discharge in an electrically neutral tube of ionised gas was initially reported by Tonks and Langmuir

[1] in 1929.

$$= \underline{\omega p}\ 2\pi$$

This created a blazing ionised gas. In order to overcome the binding potential energy, the atoms or molecules of a solid or liquid must gain enough thermal kinetic energy by heating. The resulting phase transition reveals the pressure-dependent temperature constant. Latent heat is the energy needed to cause a phase change. When there is enough energy, the molecular binding energy of a material is the same as the sum of its particles' temperature kinetic energies. So, if enough energy is added, the molecules will break apart and the material will change from a solid to an atomic gas. As opposed to being a thermodynamic phase transition, the change from gas to plasma happens gradually as temperature is raised [2, 3].

Macroscopic neutrality

As long as nothing moves the plasma from outside it, it remains electrically neutral. The plasma has no net electric charge since these forces are not present. The space, that the ionized particles take up, inside of the plasma is relatively small compared to regular lengths. Density and temperature are examples of large-scale parameters that both drive changes in the characteristic length and number of ionised particles. On a large scale, electrical neutrality holds only at distances at which the electrostatic potential energy caused by the separating of charges is more or less equal to the energy of the thermal motion that is trying to upset neutrality. This is on the same scale as the “Debye length,” which is a length scale that is characteristic of plasma. Charged particles

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indeed screen electrostatic forces up to a distance on the order of Debye length. This leads to the shielding of the electric field due to the collective behavior of the plasma particles. The shielding distance was first calculated by Debye. The Debye length (D) is directly proportional to √T and inversely proportional to the square root of density (N). where ne is plasma density; and is given as.; $\lambda_D = [\frac{s0KbT}{}]^{1/2}$, where ε_0 = permittivity of free nee space, KB = Boltzmann constant, n_e = plasma density, e = electronic charge and T =temperature” [2, 3].

Plasma frequency

One important property is the consistency of the macroscopic charge neutrality of the plasma. When plasma state suddenly out of equilibrium, the space charge field inside plasma generates collective motion of particles. The question now is what makes the charge return to its original state. The natural oscillation frequency of these collective motions is called plasma frequency [2, 3]. Because collective oscillations occur with a very high frequency, they have trouble keeping up with the motion of the electrons. Coulombic attraction between the electrically charged ions and the electrons provides this collective restoring force when the electrons oscillate around the heavy ions in a ring. The collective electron oscillation has an angular frequency of nee2 1⁄2 called plasma frequency ω_p, is given by: ω_p =* 0 +. The density of the plasma is a crucial characteristic that affects the frequency of the plasma. Since the mass of each electron is so little, we may deduce that the plasma frequency must be very high. Using the values of various parameters, $V_p > V_n \approx 9\sqrt{n}$, where n is plasma density per m^3. For a plasma having electron density, $n = 10^{10} m^{-3}$, we have, $V_p = 9 \times (10^{18})^{1/2} = 9 \times 10^9$ Hz = 9GHz. Frequency is largely determined by the important plasma parameters, one of which is the density of plasma. As each electron has a small mass we conclude that the plasma frequency must be very large. So, the plasma frequency is in the microwave region. As we know electromagnetic radiation of frequency smaller than the plasma frequency (ω ωp) transmits through the plasma. This property of plasma in the Ionosphere surrounding the earth was used for communication [4].

PPC

As discussed earlier that the periodic structure is a cumbersome structure, which is different from the continuous medium. This is because the resonance of waves on the surface of a periodic lattice displays the PBG in periodic structures. A lot of different things can be said about the random release of an atom in a periodic structure. An excited atom may either release photons with a low probability (in the allowed band) or enter a highly likely (and hence very long-lived) excited state [5]. In the system being studied, it can be seen that all of the dielectrics have the same shape in three dimensions. For these dielectrics, the equation that describes the energy of photons and how they bend in the ultraviolet (UV) and visible bands stays the same.

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So, the low frequency of the EMW that has been diffracted lines up with the weak Bragg reflections that are usually seen in X-ray diffraction. Predicted characteristics of photons with low energies are explored in connection to the diffraction of electrons with low energies [6]. The PBG represents a significant approach to controlling the movement of light within a specific material. Due to this feature, it can be conveniently utilized in a variety of applications and with a wide range of materials. The propagation of EMWs through a photonic crystal (PC) is influenced by many factors, such as the lattice constant, filling fraction, the geometry of the crystal and the refractive index (RI) difference. These elements are fundamental to understanding the structure and behavior of photonic crystals and their potential to preprogramed control the pathways of electromagnetic waves (EMWs) [8, 9]. The concept of thin film technology makes it feasible to fabricate a PC with one-dimensional periodic multilayer structure swiftly and efficiently. One-dimensional PCs are used in modern optics and optical engineering in such devices as optical filters, lasers, high-reflectivity (HR) omnidirectional mirrors, resonance cavities and optoelectronic integrated circuits [9–18]. The preceding studies about plasma and periodic structures offer a base for reflecting on the optical features of such structures which incorporate plasma materials. Using a PC with plasma materials may have its optical properties modified because of the tunable characteristics of the plasma materials. The attributes of the plasma substance may be altered to realize the desired PBG. For this reason, there is an ongoing study on the optical behavior of periodic structures comprised of plasma and other materials, dubbed plasma PCs, with the aim of determining what applications they might have. Plasma PC s (PPCs) are a type of dielectric material whose composition is made of alternate thin layers of plasma and a dielectric medium such as air or a vacuum. When thin films of plasma and dielectric materials are periodically deposited onto a substrate, photonic band gap (PBG) structures can be formed. The plasma PBG can be modified by varying the different material properties of plasma. These include, but are not limited to, plasma density, collision frequency, width of the plasma layer and externally applied magnetic field [19-21]. Varying these parameters enables the plasma devices to constitute and control the PBGs based on these features.

Experts have expressed concern over the increasing rate of the variation of magnetised cold plasma and dielectric materials. The presence of an external magnetic field is added concerning an ordinary plasma compared to a plasma with cold gyro-effective or cyclotron frequency. The strength of the given magnetic field to the cold, magnetised plasma specifies the rate of the gyroscopic effectiveness. Right Hand Polarisation (RHP) and Left-Hand Polarisation (LHP) both widen the closed intervals of the gyro-effective frequency of the magnetised cold plasma. The RZ of cold, magnetised plasmas varies with external magnetic field strength, electron count and their collision frequency. Because of its unique properties, magnetised cold plasmas are

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candidate materials to replace metals and dielectrics in periodic structures. Some authors have studied the optical properties of the proposed periodic structures with cold magnetizing plasma to [22–24]. Irregular band gap structures and reflection spectra are evident for the dielectric/magnetized cold plasma structures, asothermal them bear witness Kumar et al. According to [26], a one-dimensional periodic structure treated with a magnetised cold plasma could serve as a controllable narrow band TE (transverse electric) wave filter possessing a defect mode. Aly and Mohamed [27] studied the transmission characteristics of superconductors and dielectrics to determine their viability as mirrors or band-pass filters. Aghajamali [28] proposed that magnetised cold plasma-superconductor periodic layered structures could serve as high-pass filters and mirrors. Aly et al. [29] investigated the effect of an external magnetic field on the stability of two-dimensional metallic photonic crystals. Several optical devices exploit the fact that external fields can change the scattering and transmission of light through metals.

Aly et.al attempted a theoretical study on a one-dimensional periodic structure in the THz region of the frequency spectrum and its transmission qualities. On the transmittance and permittivity of the flawed one-dimensional periodic structure subjected to UV irradiation, Aly and Elsayed conducted a study. Plane wave expansion was suggested by Aly et al. to have an impact on the transmittance of two-dimensional n-doped semiconductor PC. The ultraviolet optical properties of the photonic band gap (PBG) between a superconductor and a dielectric were studied by Aly. Periodic dielectric and superconductor structures were investigated by Aly et.al [34]. A system of reflectors developed by Aly and Sayed [35] enables increased optical path length of the incident light within the absorbing layer, which is helpful for thin film silicon solar cells. A class of photonic crystals comprised of superconductor and semiconductor metamaterials was analyzed by Aly et al. [36]. The omnidirectional band gap of the one-dimensional magnetized complete plasma photonic crystals can be modified by changing the thickness and plasma density of the layers as noted by Dehnavi et.al. [37]. The unique one-way absorbing property together with splitting of the polarization in ultra-wide band plasma photonic crystals was studied by Ma et.al [38]. Much will be gained in the pursuit of one-way reconfigurable functionalities from these results. Recently, Soleimani and other collaborators analyzed whether band gap engineering in a nonMCP-dielectric multilayer structure could provide new possibilities for the realization of multichannel filters.

Theoretical model

In this paper, we have calculated the electric permittivity of the plasma using the MEs The RI of the plasma is computed from the electric permittivity of the plasma. The optical characteristics of the plasma PC s with And TMM has been studied while changing the parameters of the plasma.

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The electric permittivity of MCP

Magnetized-plasma

Inside of a plasma, its interaction with magnetic field is known as magnetized plasma. In other words, the study of internal wave electromagnetic (EM) wave motion and its relation with external magnetic field is divided into two cases; class one contains the Internal wave, while class two contains the external magnetic (EM) wave [4]. Case 1: This occur when the both ion and electron plasmas are taken in consideration (two fluid model) and also in hydromagnetic waves, in which the direction/ polarization of the wave is perpendicular to the static magnetic field [4]. A hydromagnetic wave is divided into Alfven waves and magnetoionic waves. In these two cases we consider the magnetic field lines perpendicular to the wave direction. Two examples of this may be seen below:

- **(a)** "EM wave perpendicular to the magnetic field ($\vec{k}$ ß $\vec{B}$). This case is also two subcases. These are (i). ($\vec{E}$ " $\vec{B}$), when electric field is parallel to the magnetic field is called the *ordinary waves* and (ii) ($\vec{E}$ ß $\vec{B}$), when electric field is perpendicular to the magnetic field is called the *extraordinary wave*
- **(b)** EM wave parallel to the magnetic field ($\vec{k}$ " $\vec{B}$). This case is also two subcases. These are(i) Right hand circular wave (R-wave). (ii) Left handed circular wave (L- wave).

To determine the wave equation in electron plasma fluid, we consider the EM wave parallel to the magnetic field. We start the MEs, these equations are:

$$\vec{A} \times \vec{E} = -\frac{6\vec{B}}{6t} \quad (3.1)$$

Results and discussion

Band structure and transmittance of a periodic structure comprised of dielectric and magnetised cold plasma were computed. We show the band structure and transmittance of the periodic structure vs frequency (GHz) as a function of plasma characteristics like B, ne and the external magnetic field plays a significant role in the MCP due to its positive and negative values when acting as right- and left-hand polarisations. Moreover, all transmittance values related to the band structure for RI nA equals 1 (air) and dA equals 12mm have been calculated and the RI of the MCP has been retrieved from Eq. (3.15) and the thickness of the MCP layer is set to d B 15mm [19]. Air with right-hand polarization possesses a periodic structure called a right-hand polarization structure, while the air with left-hand polarization possesses a left-hand polarization structure. In Figure 3.2, the response of transmittance versus frequency (GHz) for right-hand polarization is presented along with an oscillation of the MCP magnetic field B=0.4 Tesla, set at B=0.5 Teslas and B=0.6 Teslas. The electron density of MCP is fixed at ne=8 x 1017/m³ and the effective collision frequency is γ=107 Hz. For varying domains of the magnetic field, the band structure comparison with frequency (GHz) shows two gap features, In principle,

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these remarks denote that for lower values of the external magnetic field, the band edge at low frequencies changes relatively little while the band edge at high frequencies is altered very substantially by the external magnetic field. Band gaps are present within the external magnetic field's low and high frequency values. Modifications to the band edge increase the frequency range of the band gap, which, in turn, changes the transmittance value for the defined periodic structure. Figure 3.2(b) displays the relationship between transmittance and frequency in gigahertz (GHz), illustrating how the findings obtained correlate to various levels of the magnetic field (B=0.4Tesla, B=0.5Tesla, B=0.6Tesla).

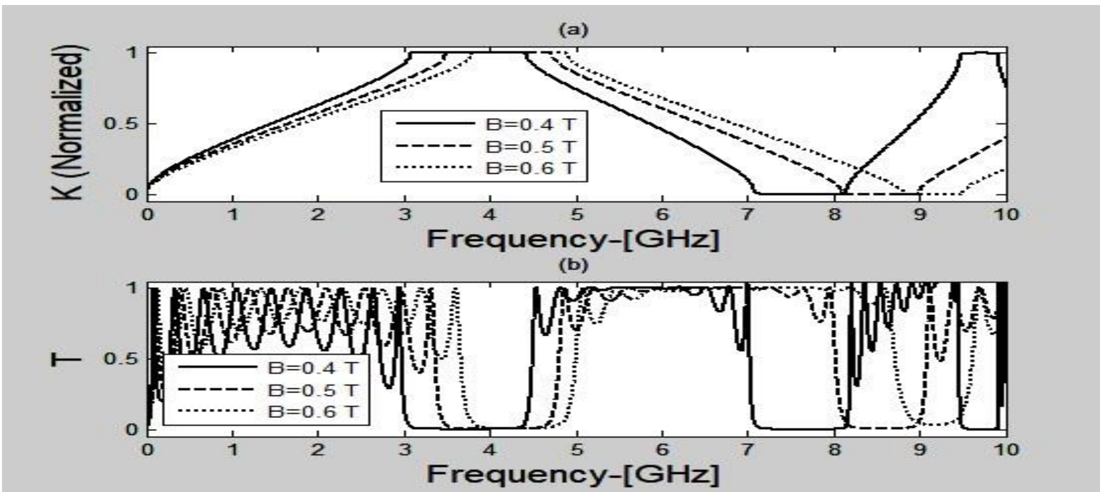

Figure 1: "(a) Dispersion relation and (b) Transmittance vs frequency charts for right-hand polarisation MCP magnetic field variations."

With a fixed plasma density of ne = 8 x 1017 m3 and ECF = 107 Hz, Figure 3.2 depicts the band structure and transparency in left-hand polarisation configuration for three different magnetic field strength values. The periodic pattern under investigation shows a band gap dependence on frequency. One can observe a low-frequency band gap (0-2.5GHz), which is responsive to the strength of the external magnetic field and another at higher frequencies (67.2GHz), which is also field-dependent. From transmission measurements made on the periodic structure, we found that it behaves as a broadband reflector and an adjustable narrow band filter within certain intervals of frequency. Specifically, it behaves this way above 0 to 2.5 GHz and from 6 to 7.2 GHz. The structure's band gap characteristics and the transmission measurements were used to arrive at these conclusions. This research indicates that at lower magnetic field strengths (B= 0.4 Tesla) and lower frequencies, the left-hand polarisation structure operates better as a broadband absorber or high pass filter than other periodic patterns examined.

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The left-handed polarization structure's photonic crystal application as a narrow, tunable filter for a wide array of frequencies and different magnetostatic fields is illustrated in Fig. 3.3 (b).

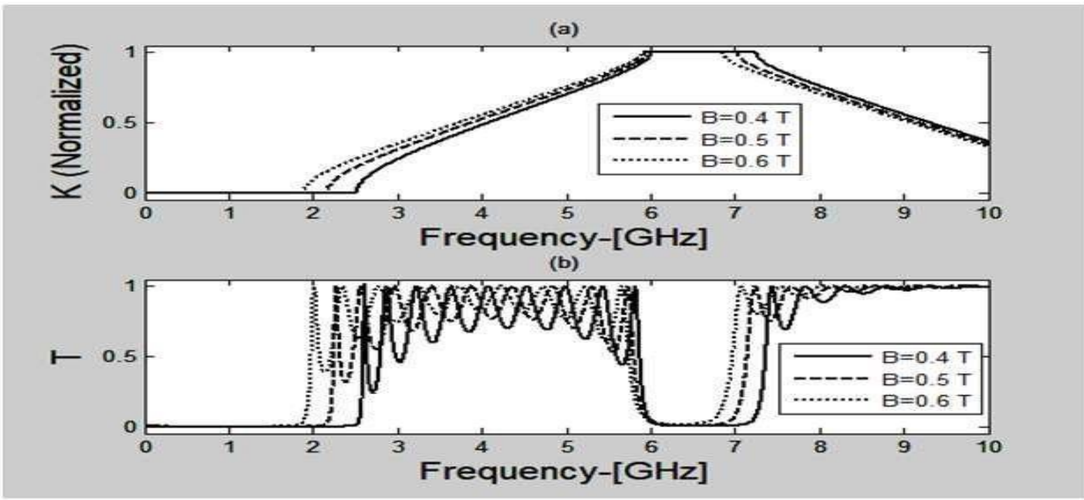

Figure 2: (a) Dispersion relation and (b) Left-handed polarisation transmission against frequency versus magnetic field of the MCP plots.

In Figure 2 (a), we study the right-hand polarisation configuration with a constant magnetic field of B = 0.6 Tesla and an effective collision frequency (ECF) of 107 Hz. This is done using the band gap structure and the graphs of transparency and frequency. We study the outcomes when the plasma density 17 e ne 17 is 8, 12 and 16 x 10 /m3. Let's fix the strength of the magnetic field (B = 0.6 Tesla) and the effective impact frequency (ECF = 107 Hz) as the plasma density increases from the lowest value of ne = 8 x 1017/m3 to the highest value of ne = 16 x 1017/m3. The band gap in the right-hand polarisation structure shifts in frequency. In addition, we also studied the transmission of the right-hand polarisation structure, which corresponds to the band gap for these concentrations of plasma. Figure 3.4(b) displays the dependences of the right-hand polarisation structure's transparency on the plasma density. This thus provides a narrow, variable multichannel filter. We examined the bandgap structure and transparency of left-hand polarization at a constant magnetic field (B=-0.6 Tesla) and effective collision frequency (ECF = 107 Hz) for plasma densities of, ne=8x1017/m3, 12x1017/m3, 16x1017/m3. It was found that the bandgap of the periodic structure shifts toward lower and higher frequencies as the plasma density increases. Left-hand polarization possesses some form of transparency at both low and high frequencies; these ranges seem to be contradictory. The proposed periodic structure behaves like a high band reflector/high-pass filter for various plasma densities in the lower frequency range. Meanwhile, it behaves like a tunable narrow-band filter in the higher frequency range.

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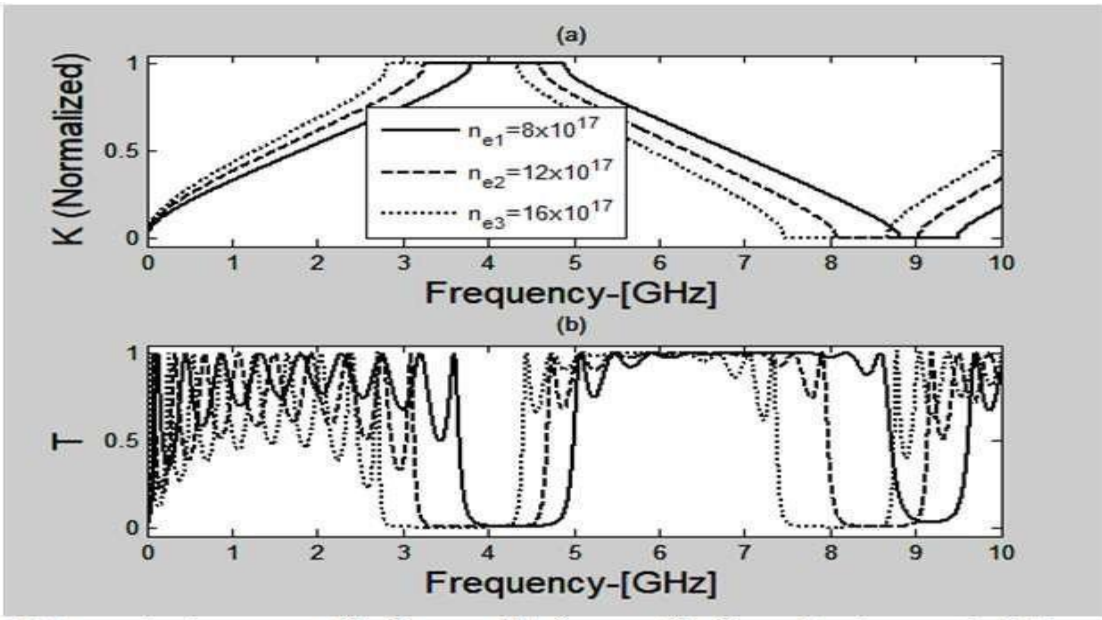
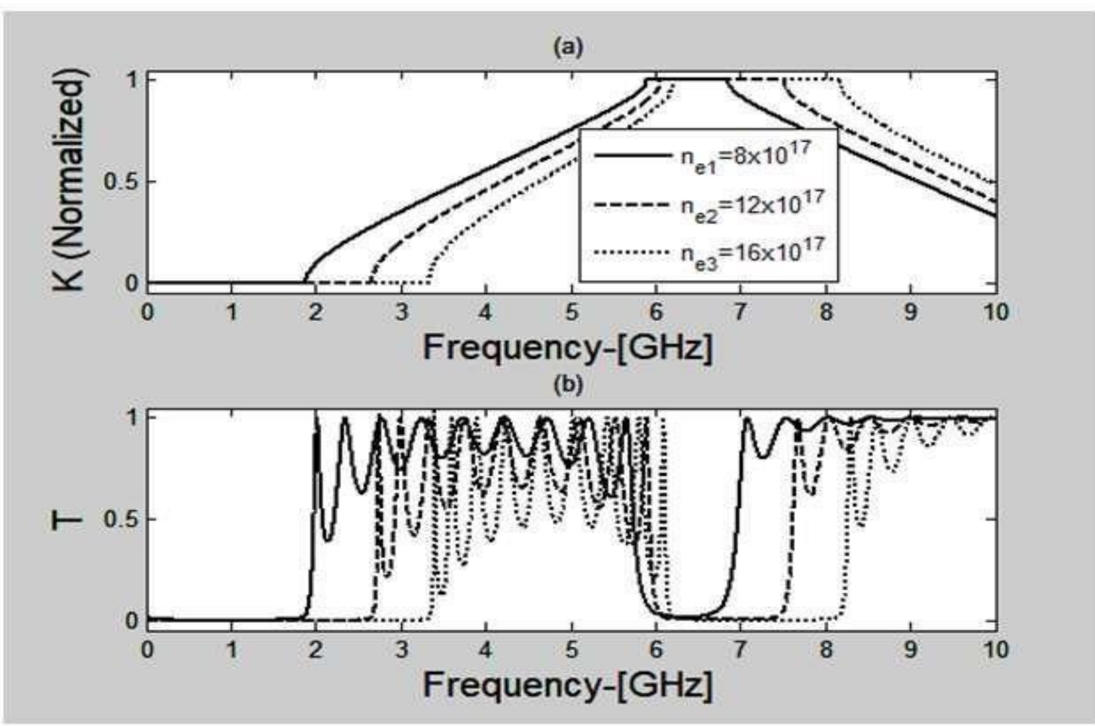


Figure 3: (a) Dispersion relation and (b) Transmittance versus frequency plots with varying plasma density of the MCP for right-hand polarization



Figures 4 and represent the band gap structure of the RH polarisation and the LH polarisation structure's transmission vs frequency (GHz) plots. All three graphs demonstrate what

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happens when 1 = 1 x 106 Hz, 2 = 5 x 106 Hz and 3 = 1 x 107 Hz. The B field is always at B=0.6 Tesla. The cold, magnetized plasma has an electron density of ne=8x1017.

The band structure and transparency were not affected by varying the effective impact frequency in the magnetised cold plasma for the right-hand polarisation structure. At the same time, the magnetic field and electron density were kept constant. Figure 3.6(a) shows a band gap with the absence of transmission between 3.8 and 4.9 GHz. This is further supported by the fact that the changes in the frequency values between these bands are also found to be very small. Likewise, we did effective impact-frequency change and observed the band gap structure and transmission versus frequency (GHz) graphs of the left-hand polarisation structure. The band gap and transparency of the periodic structure were further investigated by effective impact frequencies of different values (1 = 1x106Hz, 2 = 5x106Hz and 3 = 1x107Hz). A magnetic field with B=-0.6 Tesla was constant throughout and cold, magnetised plasma with ne=8x1017 was used. The printouts with varying effective collision frequency demonstrate its slight impact with respect to the band gap and transmission in considered periodic structure with lower (0-1.9GHz) and higher (5.9-6.9GHz) frequencies during the lefthand polarization structure. These results are shown in figures.

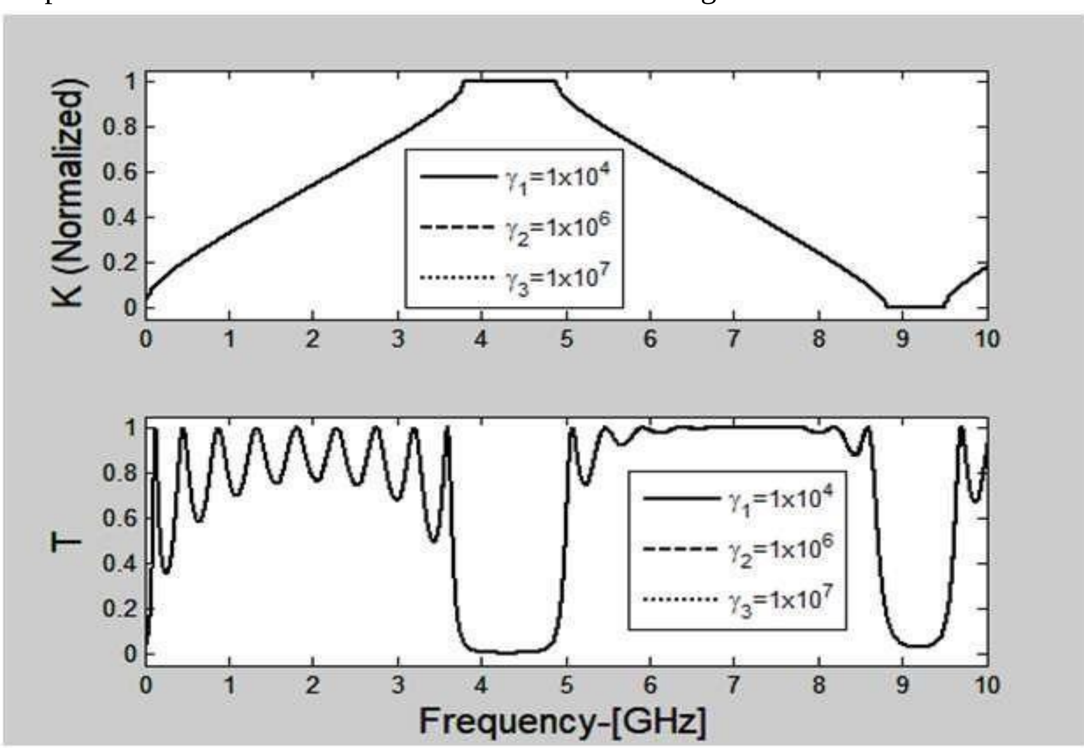

Figure 5: (a) Dispersion relation and (b) Transmittance versus frequency plots with varying ECF of the MCP for right-hand polarization

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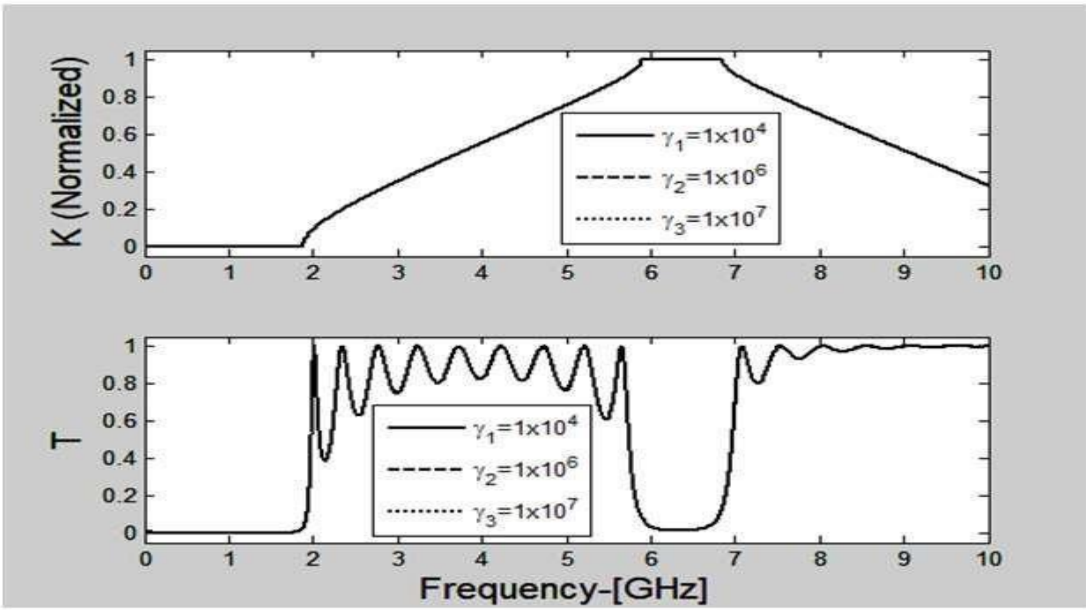

Figure 6: (a) Dispersion relation and (b) Transmittance versus frequency plots with varying ECF of the MCP for left-hand polarization

Conclusion

In this work, a theoretical investigation of one-dimensional plasma photonic crystals (PPCs) composed of alternating layers of air and magnetized cold plasma (MCP) has been carried out using the Transfer Matrix Method (TMM). The frequency-dependent dielectric permittivity of the magnetized plasma was derived from Maxwell's equations, incorporating key plasma parameters such as plasma frequency, cyclotron frequency, electron density, collision frequency and the externally applied magnetic field. From this permittivity, the effective refractive index of the plasma layer was obtained, enabling the calculation of the photonic band structure and transmission characteristics of the periodic system. The results clearly demonstrate the formation of tunable photonic band gaps (PBGs) in the microwave and GHz frequency ranges for both right-hand polarization (RHP) and left-hand polarization (LHP) configurations. It was found that the external magnetic field and plasma electron density play dominant roles in shifting the band edges and controlling the width and position of the band gaps. In particular, variations in the magnetic field lead to significant changes in the high-frequency band edges, while changes in plasma density cause systematic shifts of the band gaps over a wide frequency range. In contrast, the effective collision frequency was observed to have only a weak influence on the band structure and transmission spectra. Furthermore, the transmission analysis reveals that the proposed periodic structure can function as a broadband reflector in certain frequency intervals and as a narrow-band, tunable filter in others, depending on the polarization state and plasma parameters. The

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polarization-dependent behavior of the MCP layers enables selective control of electromagnetic wave propagation, offering additional flexibility in device design. Overall, the studied magnetized cold plasma photonic crystal exhibits strong reconfigurability and tunability, making it a promising candidate for advanced microwave and terahertz photonic devices, including tunable filters, band-stop and band-pass components, polarization-selective elements and reconfigurable electromagnetic wave control systems.

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