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About Tunable Ternary Warm Magnetized Plasma Photonic Crystals

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ABSTRACT

In this study, the propagation of electromagnetic (EM) waves and band gap structure in a one-dimensional ternary plasma photonic crystal (PPC) is investigated. The unit cell of the structure consists of dielectric I-plasma-dielectric II and an external constant magnetic field is applied perpendicular to the PPC boundary. In under study PPC, effects of thermal velocity of plasma electrons are taken into account as a dissipative factor. This structure irradiated by obliquely incident linear EM wave, but right-handed and left-handed waves are propagated with different velocities due to existence of DC magnetic field along the wave vector; and therefore, the well-known Faraday rotation effect occurs. The dispersion relation, band gap structure and absorption of the electromagnetic wave will be studied for right-handed waves. It will be shown by changing different parameters such as intensity of the external magnetic field, filling factor and the electron thermal velocity of the plasma layer and dielectric constant of the dielectric layer, the width, number and the location of band gaps can be adjusted.

1. Introduction

Recently, the use of plasma in research and industrial applications of materials has received much attention. One of these fields is the application of plasma in the structure of photonic crystals (PC), where the use of plasma mediums offers significant advantages over other materials. Photonic crystal is a structure with periodical arrangement which composed of two or more materials with different dielectric constants. The photonic crystals show special and peculiar optical properties, the most interesting of which is the existence of photonic band gaps (PBGs). PBGs are the frequency domains in which the electromagnetic wave cannot propagate and by changing the parameters of photonic crystal, for example the thickness and the dielectric permittivity of layers, the peaks and gaps of the photonic band can be varied [1]. Devices made on the basis of photonic crystals have extensive applications in sensors, refractometric and optical communication systems such as waveguides, antennas, optical filters and feedback mirrors [2-6]. To make optical waveguides as one of the most important elements of optical devices, photonic crystals are used in order to reduce reflection and losses of waveguide [7]. Recently, photonic crystals have been the focus of scientists' attention because of showing new features and numerous applications by replacing dielectric with new materials such as graphene, semiconductor, liquid crystal, plasma, and metamaterial [8-11].

Nowadays, in the practical applications of optical devices, it is necessary to make the photonic band structures controllable. In order to make the tunable photonic crystal, at least one of the components of the structure must be dependent on external factors. Tunable PCs such as structures including liquid crystals, semiconductors or piezoelectrics whose dielectric constants can be varied by applying an external electric field or by altering temperature and strain, have been considered and investigated [9-18]. One of the materials whose dielectric permittivity can be controlled by various external factors are plasmas. The plasmas are dispersion mediums whose dielectric permittivity depends on parameters such as collision frequency, plasma frequency or cyclotron frequency. These parameters can be adjusted by external electric- and magnetic- fields. Using of plasma layers in

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photonic crystals is an intelligently way that was first proposed by Hojo and Mase [19]. The response of PBSs to electric or magnetic field is much faster compared to the response to temperature or tension changes and this is a very important and effective feature in using plasma in photonic crystal structures [20]. Jank and colleagues showed that PPCs can be used as narrow filters [21]. Guo studied the dispersion relation for the oblique incident of electromagnetic wave to a one-dimensional plasma photonic crystal, and he discussed about the effects of the incident angle, collision frequency and dielectric constant of dielectric layer on dispersion equation [22]. In 2015, the first paper on the Faraday effect in plasma crystal photonics was published and shown Faraday rotation can be tuned by using this structure [23].

In this study, we use the transfer matrix method to investigate the reflection and absorption coefficients, and dispersion equation of a ternary plasma photonic crystal including the magnetized plasma layer with considering thermal effects for the first time. The results reported in previous works are applicable to the PPCs with cold plasma. In plasmas produced through the interaction of the high-power electromagnetic radiation with solid structures, temperature of electrons can reach values above 1 keV. Therefore, taking into account the thermal effects of the plasma layer become important in order to understand how the PPC's response to electromagnetic waves. It will be shown the photonic band structures can be tuned by plasma parameters, and external magnetic field due to Faraday rotation effect. Also influence of the dielectric layers' characteristics on the reflection and absorption coefficients will be examined.

2. Configuration And Basic Equations of Problem

The structure under study in the present work is a one-dimensional magnetic plasma photonic crystal, as shown in Fig. 1. The structure consists of the dielectric I, plasma and dielectric II, which are arranged periodically in the Z-direction.

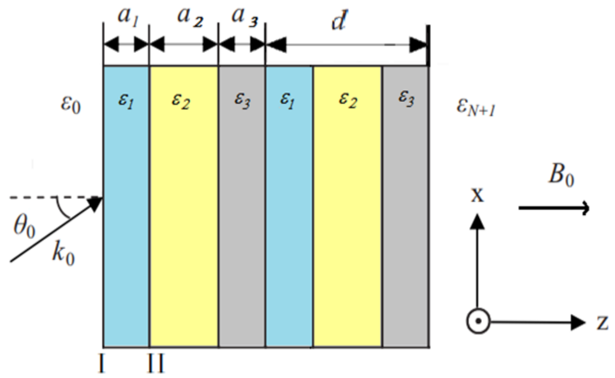

Fig. 1. Schematic view of obliquely incident electromagnetic wave in 1Dmagnetized PPC, where external magnetic field is applied along z-direction

Here, incident wave vector k_0 with incident angle θ_0 is in the xoz plane and an external magnetic field applied along z-direction. The plasma layer of the photonic crystal has been considered nondegenerate, collisionless and dissipative due to a weak thermal motion of electrons. In the presence of the constant magnetic field and taking into account of thermal effects, the dielectric permittivity tensor of the plasma is anisotropic and has an anti-Hermitian part as follows [24]:

$$\varepsilon_p = \begin{pmatrix} \varepsilon_1 & ig & 0 \\ -ig & \varepsilon_2 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix} \quad (1)$$

$$\varepsilon_1 = 1 - \frac{\omega_p^2}{\omega^2 - \omega_c^2} + i\sqrt{\frac{\pi}{8}}\frac{\omega_p^2}{\omega\,|k_z|v_T}[exp(-\frac{(\omega-\omega_c)^2}{2{k_z}^2 v_T^2}) + exp(-\frac{(\omega+\omega_c)^2}{2{k_z}^2 v_T^2})]$$

$$\varepsilon_2 = 1 - \frac{\omega_p^2}{\omega^2 - \omega_c^2} + i\sqrt{\frac{\pi}{8}}\frac{\omega_p^2}{\omega\,|k_z|v_T}\left[exp\left(-\frac{(\omega-\omega_c)^2}{2{k_z}^2 v_T^2}\right) + exp\left(-\frac{(\omega+\omega_c)^2}{2{k_z}^2 v_T^2}\right)\right] + i\sqrt{2\pi}\frac{\omega_p^2 k_x^2 v_T}{\omega\omega_c^2|k_x|}exp(-\frac{\omega^2}{2v_T^2k_z^2})$$

$$\varepsilon_3 = 1 - \frac{\omega_p^2}{\omega^2} + i\sqrt{\frac{\pi}{2}}\frac{\omega\omega_P^2}{|k_z|^3 v_T^3}exp\left(-\frac{\omega^2}{2v_T^2k_z^2}\right)$$

$$g = -\frac{\omega_c\omega_p^2}{\omega(\omega^2-\omega_c^2)} + i\sqrt{\frac{\pi}{8}}\frac{\omega_P^2}{|k_z|\omega v_T}[exp\left(-\frac{(\omega-\omega_c)^2}{2k_z^2v_T^2}\right) - exp\left(-\frac{(\omega+\omega_c)^2}{2k_z^2v_T^2}\right)]$$

In Eq.1, $k_x = k_{2x} = k_2 sin\theta_2 = \frac{\omega}{c}\sqrt{\varepsilon_+}sin\theta_2$,Index 2 refers to the plasma layer Here, ω is the incident wave frequency,v_T presents the electron thermal velocity, $\omega_P = \sqrt{\frac{n_e e^2}{m_e\varepsilon_0}}$ is the electron plasma frequency and $\omega_c = (e\,B_0)/m_e$,is the electron cyclotron frequency, where e is the electric charge of the electron and n_e, m_e are the number density and mass of the electron, respectively.

As well-known, a linearly polarized wave propagating in a magnetized plasma is decomposed into a pair of right- and left-handed circularly polarized waves, because these two polarizations move with different speeds in the magneto-active plasmas. Therefore, if a plane electromagnetic wave with electric field $\vec{E}(\vec{r},t) = \vec{E}_0 exp(i\vec{k}\cdot\vec{r} - i\omega t)$ incident to the magnetized plasma, the plane of polarization rotates as a function of distance in the direction of propagation. This phenomenon is known as Faraday rotation and its amount depends on the plasma density and applied magnetic field strength; accordingly, the effective permittivity of magnetized plasma is different for left-handed ($\boldsymbol{\varepsilon}_-$) and right-handed waves ($\boldsymbol{\varepsilon}_+$), and are given by Appleton's equation [25]. As known, when a wave irradiates from one medium to the boundary of another medium, a part of it transmits the boundary and the other part of the wave is reflected. If the medium is dissipative, part of the wave will be absorbed by it. On the other hand, by using Maxwell's equations, the relationship between the electric and magnetic field components of the wave can be obtained. The transfer matrix method is a well-known method to determine the photonic band gap and transmission, reflection and absorption coefficients in photonic crystal structures. In the following, we will calculate the transfer matrix of the one-dimensional ternary dissipative magnetized PPC structure to obtain the dispersion spectrum and the reflection and absorption coefficients of the incident electromagnetic wave. In this article, right-handed waves are investigated. The computing method for the left-handed waves is similar.

The transfer matrix for the dielectric layers is as following form:

$$M_j = \begin{pmatrix} \cos(k_{jz}a_j) & \frac{-i}{\eta_j}\sin(k_{jz}a_j) \\ -i\eta_j \sin(k_{jz}a_j) & \cos(k_{jz}a_j) \end{pmatrix} \quad (2)$$

where Index j=1,3 represents the first and the third mediums in a period, i.e. dielectric I and dielectric II respectively. In Eq.2 a_j is the width of the dielectric layer j and η_j and k_{jz} are defined as follows:

$$k_{jz} = k_j cos\theta_j = \frac{\omega}{c}\sqrt{\varepsilon_j} cos\theta_j$$

$$\eta_j = \sqrt{\frac{\varepsilon_0}{\mu_0}}\frac{\sqrt{\varepsilon_j}}{cos\theta_j}$$

The transfer matrix of the plasma layer is as follows:

$$M_2 = \begin{pmatrix} \cos(k_{2z}a_2) & \frac{-i}{\eta_2}\sin(k_{2z}a_2) \\ -i\eta_2 \sin(k_{2z}a_2) & \cos(k_{2z}a_2) \end{pmatrix} \quad (3)$$

Index 2 represents the second medium in a period, i.e. plasma, and η_2 and k_{2z} are defined as follows:

$$k_{2z} = k_2 cos\theta_2 = \frac{\omega}{c}\sqrt{\varepsilon_+} cos\theta_2$$

$$\eta_2 = \sqrt{\frac{\varepsilon_0}{\mu_0}}\frac{\sqrt{\varepsilon_+}}{cos\theta_2}$$

The matrix M, for one period, is obtained as follows:

$$M = M_1 M_2 M_3 \quad (4)$$

Finally, the transfer matrix for the ternary PPC structure with N periods is calculated as follows:

$$M = (M_1 M_2\, M_3)^N \quad (5)$$

The reflection, transmission and absorption coefficients are defined in the following form:

$$R = |r|^2$$
$$T = \frac{\eta_{N+1}}{\eta_0}|t|^2 \quad (6)$$
$$A = 1 - R - T$$

where

$$r = \frac{m_{11}\eta_0 + m_{12}\eta_0\eta_{N+1} - m_{21} - m_{22}\eta_{N+1}}{m_{11}\eta_0 + m_{12}\eta_0\eta_{N+1} + m_{21} + m_{22}\eta_{N+1}}$$

and

$$t = \frac{2\eta_0}{m_{11}\eta_0 + m_{12}\eta_0\eta_{N+1} + m_{21} + m_{22}\eta_{N+1}} \quad (7)$$

Here, m_{ij}, are the elements of the final matrix M. In the present work, the incident wave is considered with TM polarization and therefore $\eta_0 = \frac{\sqrt{\frac{\varepsilon_0}{\mu_0}}}{\cos\theta_0}$ that is related to the medium in the input plane. On the other hand, $\eta_{N+1} = \sqrt{\epsilon_{N+1}}\frac{\sqrt{\frac{\varepsilon_0}{\mu_0}}}{\cos\theta_{N+1}}$ is considered for the medium in the output plane, and ϵ_{N+1} is relative dielectric permittivity of output plane. Because of both mediums outside the PPC are assumed the vacuum, it results $\eta_{N+1} = \eta_0$. Furthermore, the dispersion relation for a one-dimensional magnetized PPC is given as [26]:

$$cos(kd) = \frac{1}{2}Tr(M)$$

In above equation, Tr(M) refers to the sum of elements of the main diameter of the matrix M that obtained in Eq.4.

3. Numerical Results and Discussion

Usually, in designing various photonic crystal geometries, we are interested in obtaining structures with the widest gap width. The reason of importance of the band gap in photonic crystals is its applications in research and technology fields such as filters, waveguides, lasers, cavities and optical switches, and other optical active elements that can replace electronic active elements. One of the most interesting applications of photonic crystals is in optical fiber communications. In this field, the unique property of photonic crystals, namely the total reflection of light when its frequency is in the photonic gap range, is used, and as a result, the losses in the fiber cladding and nonlinear effects are significantly reduced. In the construction of optical waveguides as one of the most important elements of optical devices, photonic crystals can be used to reduce reflection and waveguide losses in severe bends and coupling of resonant cavities. As mentioned, PPCs have unique features, the most important of which is flexibility and tunability by changing various parameters and controllable external factors. Our goal is to investigate the effect of various parameters on the number and width of photonic gaps and the amount of energy absorption by under study PPC.

In this section, we investigate the dispersion relation, the reflection and absorption coefficients of the magnetized plasma photonic crystal by taking into account thermal effects of the plasma layers.

3.1. Influence of External Magnetic Field

First, we examine the effects of the magnetic field. Normal dispersion relation and absorption relation are presented in Fig. 2. In Fig. 2, the parameters are set as

$\theta = 20^{\circ}, v_T = 0.07C, \varepsilon_1 = 2.1, \varepsilon_3 = 4.2, N = 15,$
$a_1 = 0.3d, a_2 = 0.4d, a_3 = 0.3d$

where $d = a_1 + a_2 + a_3$ and N is the number of dielectrics I- plasma- dielectrics II periods in the structure. Here the plasma density is considered $10^{20} cm^{-3}$.

Fig. 2, shows the photonic band structures under the effect of magnitude of external magnetic fields. The real part of the propagation constant k refers to a normal PBS and the imaginary part of k shows the absorption in PBS.

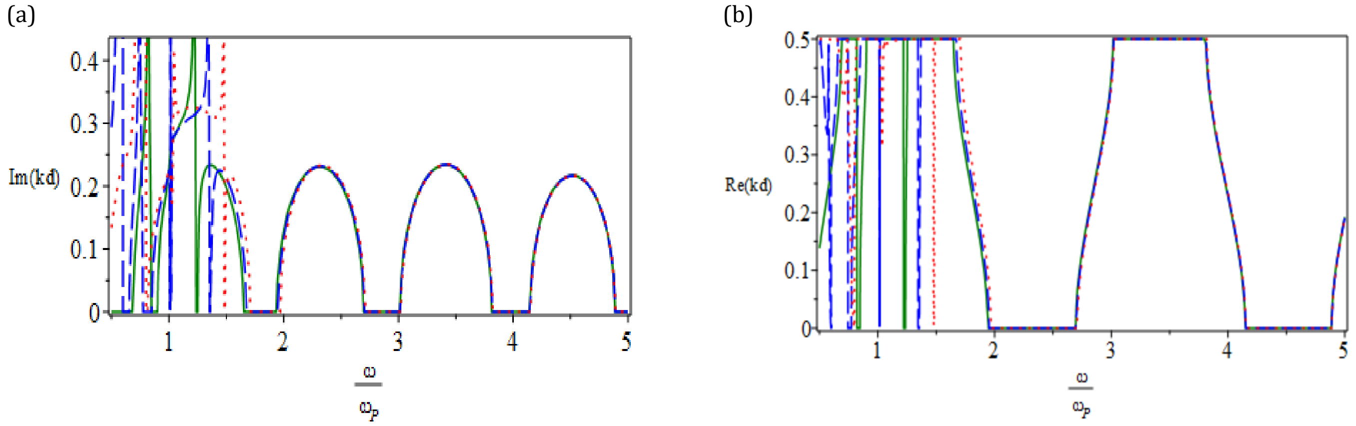

Fig. 2. Influence of external magnetic field on dispersion relation for (a)imaginary partand (b)real part. Here cyclotron frequencies are considered as ω_c=0.4ω_p (green solid line), ω_c=0.6ω_p (blue dashed line) and ω_c=0.8ω_p (red dotted line)

As seen from the figure, by varying the external magnetic field, the real and imaginary parts of the propagation constant change in condition that frequency of incident wave is below the plasma frequency. While by increasing frequency of incident wave beyond ω=1.5ω_p, changing the external magnetic field, no significant changes are observed in the PBS diagrams, because in this situation modulation degree of the external magnetic field is weak.

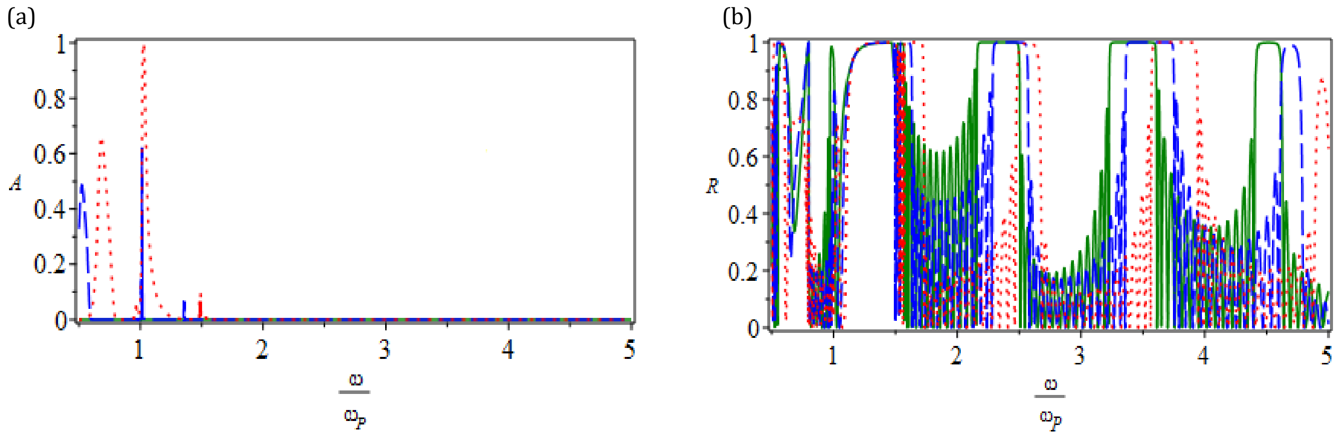

Fig. 3. Influence of external magnetic field on (a) absorption coefficient and (b) reflection coefficient. Here cyclotron frequencies are supposed as ω_c=0.4ω_p (green solid line), ω_c=0.6ω_p (blue dashed line) and ω_c=0.8ω_p (red dotted line)

The effect of the intensity of the external magnetic field on the absorption and reflection coefficients of the photonic crystal is drawn in Fig. 3. It can be seen that as the cyclotron frequency increases, the absorption intensity of the EM wave increases.

This phenomenon is more evident at low frequencies, because at high frequencies, the changes of cyclotron frequency are negligible compared to incident wave frequency.

On the other hand, it can be seen that by increasing the intensity of the external magnetic field, the band gaps of reflection shift towards higher frequencies and their widths decrease.

3.2. Influence of Electron Thermal Velocity of Plasma

In Fig. 4, the influence of existence of warm plasma with different electron thermal velocities on band gap and absorption of the plasma photonic crystal has been shown.

Here $\omega_c = 0.8\omega_P$ and graphs of reflected and absorbed powers have been plotted for $v_T = 0.02c,\ 0.07c, and\ 0.09c$. Other parameters are same as Fig. 2. As seen, with increasing the temperature, absorption intensity enhances. Because the increase of thermal velocity of the electrons leads to increment of the dissipative effects due to random successive collisions among electrons in plasma layers. There is no significant change in the number and the width of the band gaps.

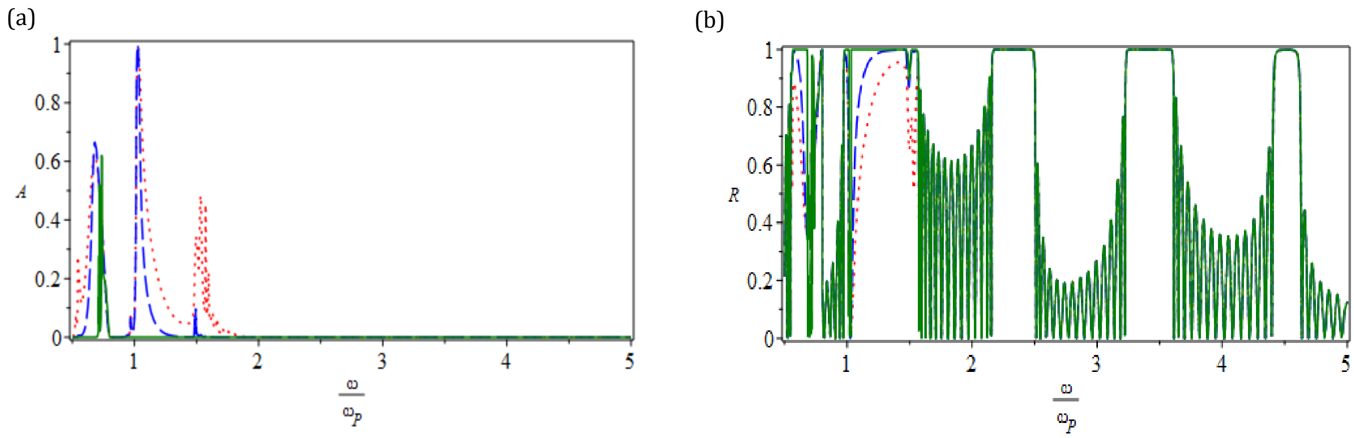

Fig. 4. Influence of electron thermal velocity of plasma on (a) absorption coefficient and (b) reflection coefficient. Here thermal velocity of electrons is supposed as $v_T = 0.02c$ (green solid line), $v_T = 0.07c$ (blue dashed line) and $v_T = 0.09c$ (red dotted line)

3.3. Influence of Plasma Layer Thickness

The effect of plasma thickness for parameters mentioned in Fig. 2 can be considered by comparing curves plotted in Fig. 5. As shown in figure 5(a), absorption peaks significantly increase by increasing the plasma layer thickness. This may be attributed to the fact that the plasma is warm, and therefore with increasing the filling factor (the ratio of plasma thickness to dielectric thickness) the absorption effect caused by the dissipating plasma increases.

Also, Fig. 5(b) shows that by varying the thickness of the plasma layer from 0.4d to 0.8d, the amount of wave reflection increases. This effect is more tangible especially at lower frequencies of the incident wave.

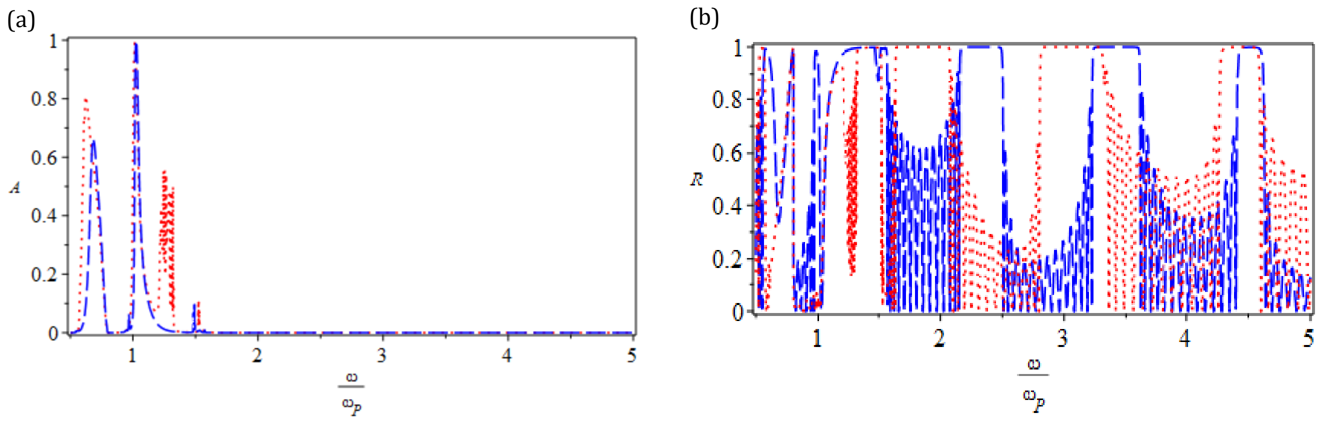

Fig. 5. Influence of thickness of the plasma layer on (a) absorption coefficient and (b) reflection coefficient. Here plasma layer thickness is supposed as $a_2 = 0.4d$ (blue dashed line) and $a_2 = 0.8d$ (red dotted line)

3.4. Influence of Dielectric Constant

In Fig. 6, the reflection and absorption curves for different dielectric constants of dielectric II,$\varepsilon_3 = 4.2$ and $\varepsilon_3 = 9.1$ and parameters supposed in Fig. 2, have been plotted.

It is important to note that dielectric permittivity $\varepsilon_1 = 2.1$, $\varepsilon_3 = 4.2$ are correspond to some available dielectric materials that have been widely used in industry ($\varepsilon_1 = 2.1$for Teflon and $\varepsilon_3 = 4.2$ for Mica). One of the important features of Mica is its layered nature and the possibility of making very thin layers of it, and for this reason it is very suitable for use in photonic crystals. Teflon has high thermal and chemical stability, that is why it is useful in making photonic crystals.

As shown in Fig. 6, increment of the dielectric constant, leads to increase of the band gap widths and increase of their number that is due to the more difference between the plasma and dielectric permittivities and consequently, more reflection and transmission areas appear [26]. Additionally, the band gap structure shifts towards lower frequencies by enhancing the permittivity of the dielectric layer. Also, Fig. 6 shows by increasing the dielectric constant, the intensity of absorption increases.

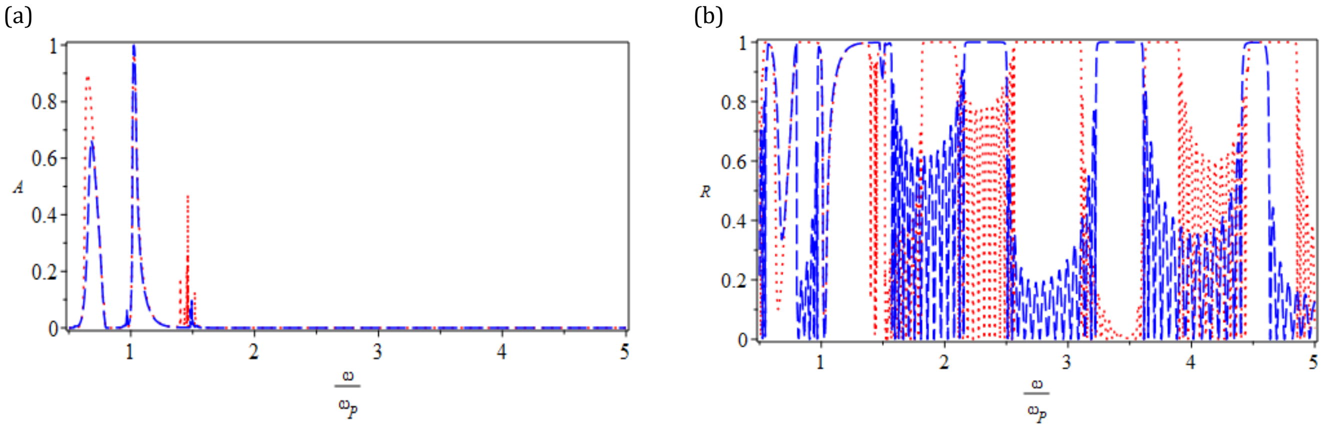

Fig. 6. Influence of dielectric constant of dielectric II on (a) absorption coefficient and (b) reflection coefficient. Here, relative permittivity of dielectric II is supposed as $\varepsilon_3 = 4.2$ (blue dashed line) and $\varepsilon_3 = 9.1$ (red dotted line)

4. Conclusions

In this research, the propagation of electromagnetic waves in a regular periodic structure (photonic crystal) was studied. Here we analyzed a 1D ternary photonic crystal including warm magnetized plasma and dielectric layers as Dielectric I-Plasma- Dielectric II. The influence of the incident wave frequency for right circular polarized waves, was considered. On the other hand, the effect of parameters of the plasma and dielectric layers such as electron temperature, filling factor, cyclotron frequency and dielectric constant of dielectric layer on the photonic band gap and absorption were determined. We showed with increasing intensity of the external magnetic field, the PBSs are shifted up wards, width of band gaps decreased and absorbed power increased. It was observed that by increasing the electron temperature of plasma, absorption increases. On the other hand, by increasing the plasma layer thickness, absorption peaks and width of band gaps increased without change in the number of band gaps. Finally, the influence dielectric constant of dielectric layers on the reflected, and absorbed powers were investigated. The results indicated that the plasma photonic crystal investigated in the present work is a tunable structure that different parameters, especially external factors, can adjust the photonic band structure and the absorption and transmission of electromagnetic waves through it.

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