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Properties of low frequency TE-electromagnetic wave in ternary plasma photonic crystal

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In this study, the oblique incident of the electromagnetic waves with frequencies lower than plasma frequency in one dimensional ternary plasma photonic crystal has been investigated. The unit cell of crystal contains a plasma layer that is embedded in two different dielectric layers. Using the wave equation, Bloch theory, and boundary condition, the dispersion relation, the group velocity and the reflection relation of the structure have been obtained. Numerical results are presented in the form of dispersion curves. The dependence of photonic band gap characteristics on plasma frequency is discussed. One attempt has been made to show how the photonic band gap characteristic of a particular structure changes when the dielectric material of the unit cell is replaced by other dielectric materials or when the incident angle of the electromagnetic wave is changed. Results show that plasma layer characteristics has a significant effect on band gaps and wave propagation characteristics; also the results show that the proposed multi-layered structure can act as a tunable photonic crystal which can be controlled by the external parameters.

Keywords: plasma photonic crystal, effective plasma frequency, photonic band gap, dispersion relation, group velocity, reflectivity.

1. Introduction

The requirements of high speed communication and the demand to keep up with the Internet's exploding need for bandwidth stimulate technologists to look for some substitutions to replace the electronic switches, that are the "bottle neck" of high speed communication systems, with faster and much smaller optical devices. A promising candidate for this are photonic crystals (PCs).

At first the concept of PCs was proposed by YABLONOVITCH [1] and JOHN [2], independently. The PCs are artificial structures with a periodic arrangement of dielectrics or metals. PCs are characterized by the unique ability to control propagation of the electromagnetic (EM) waves through a frequency band called the photonic band gap (PBG) that is analogous to an electronic band gap in conventional semiconductor crystals. So PCs drew attention of many researchers working in the field of semiconductor physics, solid state physics, optical physics, quantum optics, nanostructure, *etc*. Various studies on PCs show that these structures can have many applications such as waveguides [3–6], defect cavities [7, 8], defect-mode PCs lasers [9, 10], filters [11], omnidirectional reflectors [12, 13], high performance mirrors, PC fibers and PC superprisms, threshold-less lasers, optical switchers, optical amplifiers, *etc*. [14–20].

The PBGs of PCs suffer from being sensitive to the lattices structure. So that the PBGs cannot be changed if the dielectrics and the topology of PCs are selected. To overcome these drawbacks, in 2004, the concept of plasma photonic crystals (PPCs) was proposed by HOJO and MASE [21]. PPC is a spatial periodic structure, including plasma and dielectric. The using of plasma as multi-mode and dispersive media converted the conventional PCs to tunable structures. Because of the physical characteristics, plasma can be easily changed by many external conditions and forces [22]. Comparing with conventional photonic crystals, the plasma photonic crystals are expected to obtain many new particular characteristics. So, the study of the plasma photonic crystals is of a practical significance.

Recently, there have been a big interest in studying the propagation of EM waves in PPCs. PRASAD *et al*. have studied the properties of PBGs for waves propagating through 1D PPC with the frequency higher than that of plasma frequency [23]. Furthermore, QI *et al*. have investigated defect modes when EMs propagate through PPCs [24]. They found that the plasma density is a key quantity to manipulate the PBGs based on the transfer matrix method (TMM) [25]. GUO *et al*. studied 1D PPCs with time variation of the plasma density. They found that the PBGs can be tuned by changing time [26]. YANG *et al*. studied the effect of the incidence angle of the EM field with PPC surface on transmission characteristics in 1D PPC [27]. They understand that reflectivity has been enlarged by increasing the incidence angle. HAI-FENG ZHANG *et al*. [28] also investigated the transmission and defect modes of 1D PPCs in the presence of an external magnetic field. They found that the external magnetic field can also affect the characters of defect modes and transmission peeks. In the experiment, the PBGs of PPCs for a millimeter range and the abnormal refraction around the electron plasma frequency wave were verified and observed by SAKAI and TACHIBANA [29]. WEILI FAN and LIFANG DONG also used a dielectric barrier discharge with two liquid electrodes to obtain tunable 1D PPCs [30]. In the mentioned above research, the frequency of EM field has been considered greater than plasma frequency. The refractive index relation of plasma is $n_\mathrm{p} = \sqrt{1 - \omega_\mathrm{p}^2/\omega^2}$, where ω_p is plasma frequency (characteristic frequency for bulk plasma) and ω is the frequency of EM wave. So, for frequency greater than ω_p, EM wave can propagate through plasma when for frequencies less than ω_p, the propagation of EM wave is forbidden. But, EM waves can propagate in a PPC even at the frequencies less than ω_p due to the structural periodicity. The lowest frequency, at which wave propagation can start to happen, is defined as an effective plasma frequency $\omega_{p,\,eff}$ for a PPC system [31, 32].

In this manuscript, the propagation of EM wave with the frequency lower than plasma frequency has been investigated. We consider the case of EM wave incident on PPC surface with TE polarization. Using the transfer matrix method (TMM) [25], the dispersion and reflection, the group velocity, and the effective group index of refraction for a ternary 1D PPC have been studied. Here, the PPC are periodic layers of three different materials, namely: glass–plasma–MgF_2, then the result has been compared with the structure glass–plasma–ZnS. This manuscript is organized as follows: using TMM the dispersion relation of PPC is presented in Section 2. Section 3 is dedicated to results and discussion. Finally, conclusions are presented in Section 4.

2. Basic equations

The schematic diagram of the EM waves propagating in 1D PPCs is shown in Fig. 1. We assume that the plasma dielectric photonic crystal is divided into a number of units and each unit has three media – one of them is plasma with width b and the other are: dielectrics with width a and d, and the width unit cell $L = a + b + c$. For this periodic structure, the refractive index profiles have the below form,

$$n(x) = \begin{cases} n_1 = \sqrt{\varepsilon_1}\,, & NL < x < NL + a \\ n_p = \sqrt{1 - \omega_p^2/\omega^2}\,, & NL + a < x < NL + a + b \\ n_3 = \sqrt{\varepsilon_3}\,, & NL + a + b < x < (N+1)L \end{cases} \tag{1}$$

where $N = 0, 1, 2, ...$, and n_1 and n_3 are the refractive index of dielectrics with permittivity ε_1 and ε_3, respectively; $\omega_p = \sqrt{4\pi e^2 n_e/m}$ is the plasma frequency whose e, m and n_e are charge, mass and density of plasma electrons, respectively. Here, the spatial periodicity is defined by L so that $n(x) = n(x + L)$.

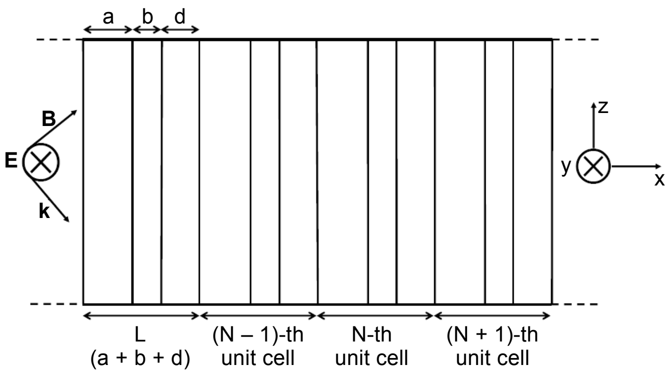

Fig. 1. The 1D structure of ternary PPC.

The Maxwell electromagnetic wave equation corresponding to the electric field of an EM wave propagating along the x-axis may be written as [25, 33]

$$\frac{\mathrm{d}^2 E(x)}{\mathrm{d}x^2} + \left[\left(\frac{\omega}{c} n_i(x)\right)^2 - \beta_i^2\right] E(x) = 0 \tag{2}$$

Here, c is light velocity in vacuum, $\beta_i = (n_i\omega/c)\sin(\theta_i)$ is the x component of the propagation constant in different layers of plasma, n_i is the refractive index of each layer and θ_i is the angle of propagation direction of the wave in any layer with normal direction. Here, the frequency of EM wave is less than plasma frequency. Therefore, solutions of Eq. (2) for three different regions of the PPC can be written as follows:

$$E(x) = \begin{cases} a_N \exp\left[ik_1(x - NL)\right] + b_N \exp\left[ik_1(x - NL)\right], & NL < x < NL + a \\ c_N \exp\left[ik_2(x - NL)\right] + d_N \exp\left[ik_2(x - NL)\right], & NL + a < x < NL + a + b \\ e_N \exp\left[ik_3(x - NL)\right] + f_N \exp\left[ik_3(x - NL)\right], & NL + a + b < x < (N + 1)L \end{cases} \tag{3}$$

where a_N, b_N, c_N, d_N, e_N and f_N are unknown constant coefficients and k_1, k_2 and k_3 are wave vectors in three regions that can be expressed as,

$$k_1 = \frac{\omega n_1}{c}\cos(\theta_1) = \sqrt{\frac{\omega^2 \varepsilon_1}{c^2} - \beta_1^2} \tag{4}$$

$$k_2 = \sqrt{\frac{\omega^2}{c^2}\left(\frac{\omega_\mathrm{p}^2}{\omega^2} - 1\right) - \beta_2^2} = \frac{\omega}{c}\sqrt{\frac{\omega_\mathrm{p}^2}{\omega^2} - 1}\,\cos(\theta_2) = \frac{\omega}{c} n'_\mathrm{p}\cos(\theta_2) \tag{5}$$

$$k_3 = \frac{\omega n_3}{c}\cos(\theta_3) = \sqrt{\frac{\omega^2 \varepsilon_3}{c^2} - \beta_3^2} \tag{6}$$

while $n'_\mathrm{p} = \sqrt{\omega_\mathrm{p}^2/\omega^2 - 1}$ and θ_1, θ_2 and θ_3 are the ray angles in each layer and are related to each other, using Snell's law, as follows:

$$\theta_2 = \cos^{-1}\sqrt{1 - \frac{n_1^2}{n'^2_\mathrm{p}}\sin^2(\theta_1)} \tag{7}$$

$$\theta_3 = \cos^{-1}\sqrt{1 - \frac{n_1^2}{n_3^2}\sin^2(\theta_1)} \tag{8}$$

For obtaining the optical properties of the proposed structure, the transfer matrix method (TMM) has been used. By imposing the continuity conditions for $E(x)$ and its derivatives $dE(x)/dx$ at boundaries, namely $x = (N-1)L$, $[(N-1)L + a]$ and $[(N-1)L + a + b]$, we obtain the system of equations containing six equations. The six equations can be rewritten as the following three matrix equations:

$$\begin{pmatrix} \exp(ik_1L) & \exp(-ik_1L) \\ k_1\exp(ik_1L) & -k_1\exp(-ik_1L) \end{pmatrix}\begin{pmatrix} a_{N-1} \\ b_{N-1} \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ k_3 & -k_3 \end{pmatrix}\begin{pmatrix} e_N \\ f_N \end{pmatrix} \tag{9a}$$

$$\begin{pmatrix} \exp(ik_3a) & \exp(-ik_3a) \\ k_3\exp(ik_3a) & -k_3\exp(-ik_3a) \end{pmatrix}\begin{pmatrix} e_N \\ f_N \end{pmatrix} = \begin{pmatrix} \exp(k_2a) & \exp(-k_2a) \\ k_2\exp(k_2a) & -k_2\exp(-k_2a) \end{pmatrix}\begin{pmatrix} c_N \\ d_N \end{pmatrix} \tag{9b}$$

$$\begin{pmatrix} \exp\left[ik_2(a+b)\right] & \exp\left[-ik_2(a+b)\right] \\ k_2\exp\left[ik_2(a+b)\right] & -k_2\exp\left[-ik_2(a+b)\right] \end{pmatrix}\begin{pmatrix} c_N \\ d_N \end{pmatrix}$$

$$= \begin{pmatrix} \exp\left[ik_1(a+b)\right] & \exp\left[-ik_1(a+b)\right] \\ k_1\exp\left[ik_1(a+b)\right] & -k_1\exp\left[-ik_1(a+b)\right] \end{pmatrix}\begin{pmatrix} a_N \\ b_N \end{pmatrix} \tag{9c}$$

The solutions of these equations can be expressed in terms of the matrix equation as follows [34]:

$$\begin{pmatrix} a_{N-1} \\ b_{N-1} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}\begin{pmatrix} a_N \\ b_N \end{pmatrix} \tag{10}$$

where A, B, C and D are the matrix elements of the unit cell transfer matrix that relates the complex amplitude of the incident wave a_{N-1} and the reflected plane wave b_{N-1} in one layer of the $(N-1)$-th unit cell to corresponding amplitudes in the next unit cell. Using boundary conditions for electric field and its derivation, the arrays of the transform matrix are given by,

$$\begin{aligned} A = {} & \frac{1}{4k_1k_2k_3}\exp(-iak_1 - bk_2) \\ & \times\Big\{ i\left[(k_1 - ik_2)^2 + \exp(2bk_2)(-ik_1 + k_2)^2\right]k_3\cos(k_3d) \\ & + 2\exp(bk_2)\sin(k_3d)\left[-ik_2(k_1^2 + k_3^2)\cosh(bk_2)\right. \\ & \left. + k_1(k_2 - k_3)(k_2 + k_3)\sinh(bk_2)\right]\Big\} \end{aligned} \tag{11a}$$

$$B = \frac{1}{4k_1k_2k_3}\exp\left\{-bk_2 + ik_1\left[a + 2(b+d)\right]\right\}$$
$$\times\left\{-i\left[1 + \exp(2bk_2)\right]k_2(k_1 - k_3)(k_1 + k_3)\sin(k_3d)\right.$$
$$\left.+\left[\exp(2bk_2) - 1\right]\left[-i(k_1^2 + k_2^2)k_3\cos(k_3d) + k_1(k_2^2 + k_3^2)\sin(k_3d)\right]\right\} \tag{11b}$$

$$C = \frac{1}{4k_1k_2k_3}\exp\left\{-bk_2 - ik_1\left[a + 2(b+d)\right]\right\}$$
$$\times\left\{i\left[1 + \exp(2bk_2)\right]k_2(k_1 - k_3)(k_1 + k_3)\sin(k_3d)\right.$$
$$\left.+\left[\exp(2bk_2) - 1\right]\left[i(k_1^2 + k_2^2)k_3\cos(k_3d) + k_1(k_2^2 + k_3^2)\sin(k_3d)\right]\right\} \tag{11c}$$

$$D = \frac{1}{4k_1k_2k_3}\exp(-iak_1 - bk_2)$$
$$\times\left\{i\left[(k_2 - ik_1)^2 - \exp(2bk_2)(ik_1 + k_2)^2\right]k_3\cos(k_3d)\right.$$
$$+ 2\exp(bk_2)\sin(k_3d)\left[ik_2(k_1^2 + k_3^2)\cosh(bk_2)\right.$$
$$\left.\left.+ k_1(k_2 - k_3)(k_2 + k_3)\sinh(bk_2)\right]\right\} \tag{11d}$$

According to the Floquet–Bloch theorem, solutions of wave equations for a periodic medium have the form $E_k(x, t) = E_k(x)\exp(-ikx)\exp(i\omega t)$ [35], where $E_k(x)$ is periodic with spatial periodicity L, so that the electric field is expressed as $E_k(x + L) = E_k(x)$. The constant k is known as the Bloch wavenumber. In terms of column vector representation and using the above mentioned theorem, the relation between amplitudes of the electric filed in two consecutive unit cells can be written as

$$\begin{pmatrix} a_N \\ b_N \end{pmatrix} = \exp(-ikL)\begin{pmatrix} a_{N-1} \\ b_{N-1} \end{pmatrix} \tag{12}$$

According to Eqs. (10) and (12), the Bloch wave must satisfy the following eigenvalue equation,

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}\begin{pmatrix} a_N \\ b_N \end{pmatrix} = \exp(ikL)\begin{pmatrix} a_N \\ b_N \end{pmatrix} \tag{13}$$

where the phase factor $\exp(ikL)$ is the eigenvalue of the unit transfer matrix (A, B, C and D) which can be described as

$$\begin{vmatrix} A - \exp(ikL) & B \\ C & D - \exp(ikL) \end{vmatrix} = 0 \tag{14}$$

Here, k is a function of ω. In the case that ω is less than plasma frequency, the dispersion for the proposed structure can be written as

$$\begin{aligned} k(\omega) = \frac{1}{L}\cos^{-1}\Bigg[& \cos(k_1 a)\cosh(k_2 b)\cos(k_3 d) \\ & - \frac{1}{2}\left(\frac{k_1}{k_3} + \frac{k_3}{k_1}\right)\sin(k_1 a)\cosh(k_2 b)\sin(k_3 d) \\ & + \frac{1}{2}\left(\frac{k_2}{k_1} - \frac{k_1}{k_2}\right)\sin(k_1 a)\sinh(k_2 b)\cos(k_3 d) \\ & + \frac{1}{2}\left(\frac{k_2}{k_3} - \frac{k_3}{k_2}\right)\cos(k_1 a)\sinh(k_2 b)\sin(k_3 d)\Bigg] \end{aligned} \tag{15}$$

The reflection coefficient of such periodic structure for N number of periods can be deduced by using the relation

$$r_N = \left(\frac{b_0}{a_0}\right)_{b_N = 0} \tag{16}$$

where a_0 and b_0 represent the complex amplitudes of the incident plane wave and the reflected plane wave, and the condition $b_N = 0$ implies the boundary condition that to the right of periodic structure there is no wave incident on it.

Using Eq. (10), we can write the following relation:

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^N \begin{pmatrix} a_N \\ b_N \end{pmatrix} \tag{17}$$

The N-th power of unit matrix can be simplified by the following matrix identity [36, 37]:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}^N = \begin{pmatrix} AU_{N-1} - U_{N-2} & BU_{N-1} \\ CU_{N-1} & DU_{N-1} - U_{N-2} \end{pmatrix} \tag{18}$$

that,

$$U_N = \frac{\sin\left[(N+1)kL\right]}{\sin(kL)} \tag{19}$$

With k given by Eq. (15), the reflection coefficient is immediately obtained from Eqs. (16)–(19) as

$$r_N = \frac{CU_{N-1}}{AU_{N-1} - U_{N-2}} \tag{20}$$

so, the reflectivity of structure is given by

$$R = \left|r_N\right|^2 \tag{21}$$

Other parameters which have been calculated in this manuscript are group velocity v_g, $n_{\text{eff, ph}}$ which is used for the effective index associated with the effective phase velocity, and effective group index $n_{\text{eff, g}}$. The group velocity can be obtained by taking derivative of $k(\omega)$ with respect to ω [38, 39],

$$v_g = \left(\frac{dk(\omega)}{d\omega}\right)^{-1} \tag{22}$$

3. Results and discussion

In this section, graphs for investigation of the properties of the mentioned above periodic structure have been plotted. Here, we introduce three normalization parameters f_1, f_2 and f_3. The parameter $f_1 = a/d$ shows the ratio of the glass layer thickness to other dielectric layer thickness. Also $f_2 = b/a$ has been introduced for indicating the thickness of the plasma layer. We have considered the normalized plasma frequency parameter as $f_3 = \omega_p b/c$.

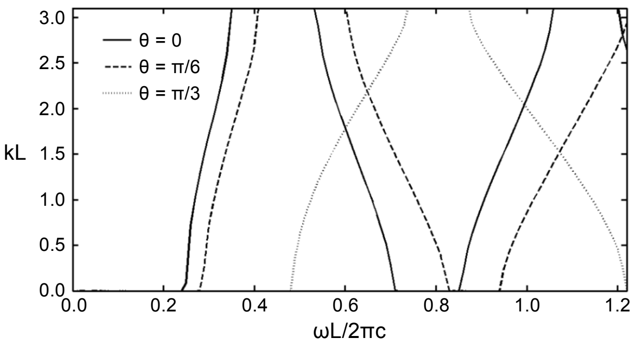

Fig. 2. Photonic band gap structure of the ternary PPC with $f_1 = 1$, $f_2 = 0.3$, $f_3 = 1$ and $n_3 = 1.38$ for different incident angles of the EM wave.

In Figure 2, using Eq. (15), the effect of the incident angle of EM wave on dispersion characteristics of PPCs is studied. Here, $f_1 = 1$, $f_2 = 0.3$, $f_3 = 1$ and $n_3 = 1.38$ have been considered. Figure 2 shows that by increasing the wave incident angle the effective plasma frequency and the starting frequency of the first pass band tend to higher frequencies. As it is clear in Fig. 2, for bigger angles the number of band gaps decreases in the same frequency interval. So that for $\theta = 0$, $\pi/6$ and $\pi/3$ there are 4, 3 and 2 band gaps, respectively. In Fig. 2, it is demonstrated that the range of allowed frequencies between two band gaps decreases when the incident angle decreases. Namely, smaller angles are more suitable for the cases when the PPCs are used as filters.

For comparison, between ternary PPCs and binary PPCs, the photonic band gap structure of the binary PPCs has been plotted. The behavior of curves is the same as in Fig. 2. With increasing incident angle, the effective plasma frequency increases but the number of band gaps decreases. When comparing Figs. 2 and 3, one finds that for ternary plasma photonic crystals, the number of band gaps is bigger than in binary plasma photonic crystals. Also, the band gaps in binary plasma photonic crystals are wider.

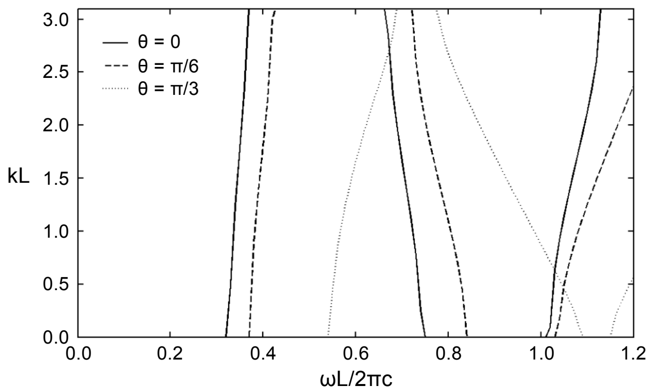

Fig. 3. Photonic band gap structure of the binary PPC with $f_2 = 0.3$, $f_3 = 2.4$ and for different incident angles of the EM wave.

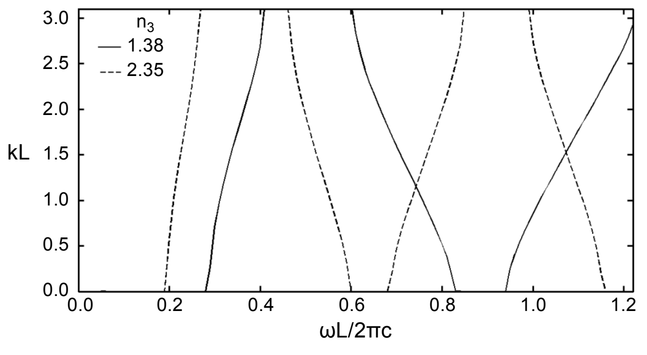

Fig. 4. Photonic band gap structure of the ternary PPC with $f_1 = 1$, $f_2 = 0.3$, $f_3 = 1$ and $\theta = \pi/6$ for two different arrangements of dielectrics, namely glass–plasma–MgF_2 and glass–plasma–ZnS.

In order to study the effects of the refractive index difference between two dielectric layers, the dispersion equation *versus* the normalized frequency for two different refractive indexes of the second dielectric layer n_3 is plotted in Fig. 4, while $f_1 = 1$, $f_2 = 0.3$, $f_3 = 1$ and $\theta = \pi/6$. It is clear that an increase in n_3 leads to an increase in the number of band gaps in the same frequency interval. Also by increasing n_3, the effective plasma frequency, approaches to red frequencies. So that for $n_3 = 2.35$ and 1.38, the normalized effective plasma frequency is 0.19 and 0.28, respectively, while the normalized plasma frequency is 1.22. Figure 4 shows that the width of band gaps decreases when the refractive index differences increase.

In Figure 5, the dispersion equation for different amounts of the plasma filling factor is plotted. Here $f_1 = 1$, $f_3 = 1$, $n_3 = 1.38$ and $\theta = \pi/6$ have been considered. Because the condition $\omega < \omega_p$ is satisfied, the range of the normalized frequency from 0 to 0.477 has been considered. Figure 5 shows that when the plasma layer width and the plasma filling factor increase, the width of band gaps decreases, but the range of pass bands increases. In this case, by increasing f_2, we observe that the normalized effective plasma frequency shifted toward red frequencies.

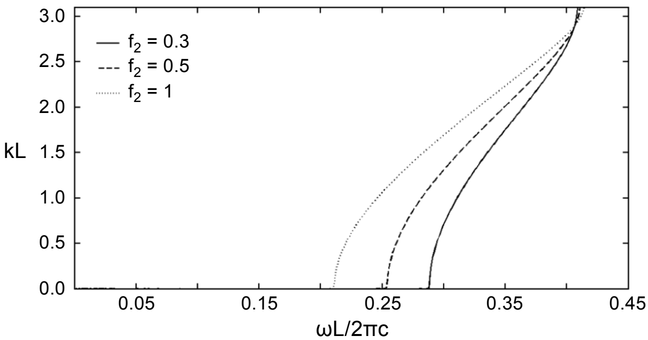

Fig. 5. Photonic band gap structure of the ternary PPC with $f_1 = 1$, $f_3 = 1$, $n_3 = 1.38$ and $\theta = \pi/6$ for different amounts of plasma filling factor f_2.

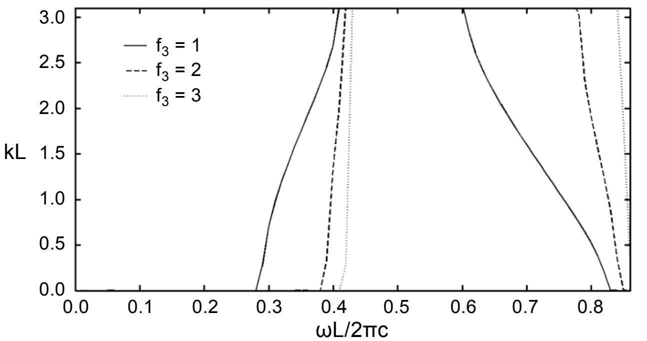

Fig. 6. Photonic band gap structure of the ternary PPC with $f_1 = 1$, $f_2 = 0.3$, $n_3 = 1.38$ and $\theta = \pi/6$ and for different amounts of factor f_3.

In order to investigate into the plasma density effects on the dispersion of structure, the dispersion equation is plotted in Fig. 6 for different f_3. The results show that the effects of increasing f_3 are against the effects of increasing the plasma filling factor in Fig. 5 because the increase in plasma density leads to the decrease in plasma refractive index and optical path length. As is clear in Fig. 6, for bigger amount of f_3, the band gaps are wider and effective plasma frequency shifts toward higher frequencies. In other words, the effect of increasing plasma density on plasma frequency is the same as its effect on effective plasma frequency. The number of band gaps for higher plasma density is bigger.

In Figures 7 and 8, the structure reflectivity *versus* the normalized frequency for $N = 10$ unit cell is plotted. In Figure 7, the effect of changing the incident angle of EM wave on structure reflectivity has been investigated. As it is clear in Fig. 7, for the frequencies in band gap ranges, according to Fig. 2, the reflectivity is one and for these frequencies we have no any transmission. Also in Fig. 8, for the incident angle $\theta = \pi/6$, the effect of refractive index difference between two dielectric layers on reflectivity has been illustrated. This should match with Fig. 2 related to dispersion.

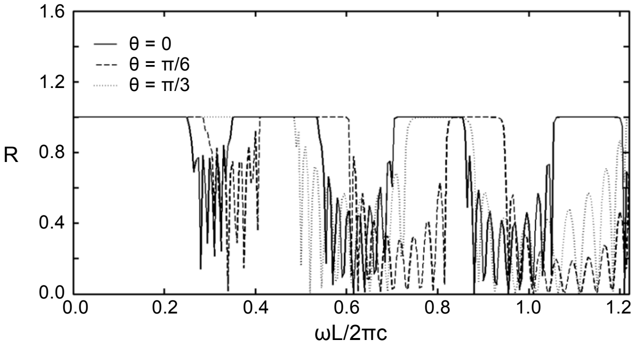

Fig. 7. Reflectivity of the ternary PPC with $f_1 = 1$, $f_2 = 0.3$, $f_1 = 1$ and $n_3 = 1.38$ for different incident angles of the EM wave.

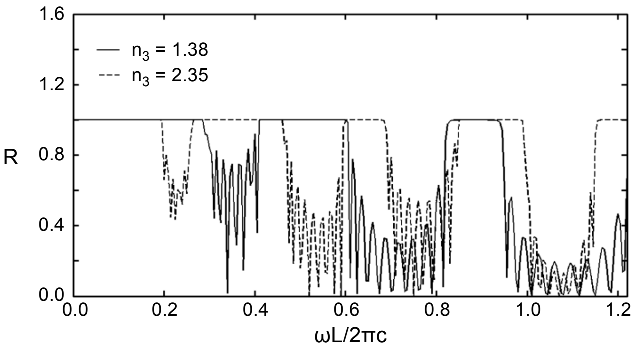

Fig. 8. Reflectivity of the ternary PPC with $f_1 = 1$, $f_2 = 0.3$, $f_3 = 1$, and $\theta = \pi/6$ for two different arrangements of dielectrics, namely glass–plasma–MgF_2 and glass–plasma–ZnS.

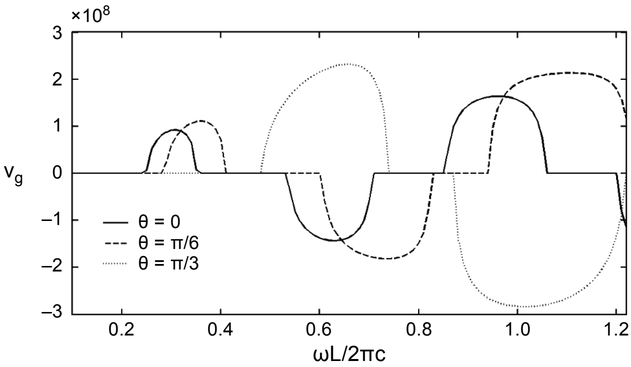

Fig. 9. Group velocity of EM wave for propagation in the ternary PPC with $f_1 = 1$, $f_2 = 0.3$, $f_3 = 1$ and $n_3 = 1.38$ for different incident angles of the EM wave.

Figure 9 shows variations of the group velocity *versus* the normalized frequency for different incident angles. It is obvious that, for larger incident angles of EM wave, the local and global maximums and minimums value of the curve are bigger. Namely, for some of the frequencies under certain incident angle, the data transfer rate is bigger. So that, for $\theta = 0$, the global maximum value of the curve is 1.639×10^8 m in $\omega L/2\pi c = 0.96$, while the global maximum value of group velocity is 2.837×10^8 m in $\omega L/2\pi c = 1.01$ for $\theta = \pi/3$. As it is clear in Fig. 9, by increasing the normalized frequency, the maximum value of the group velocity curve will increase. The slope of the dispersion relation curve in Fig. 2 confirms this fact.

4. Conclusion

In this manuscript, the propagation of EM wave with the frequency lower than the plasma frequency of plasma photonic crystal has been investigated. The results show that the propagation of the EM wave with the frequency lower than the plasma frequency in proposed plasma photonic crystal structures is possible, while in the bulk plasma propagation of the mentioned waves it is impossible. Plots show that the incident angle of the EM wave with TE polarization has a significant effect on dispersion relation, reflectivity and group velocity. The increase in the incident angle of EM leads to a blue shift of effective plasma frequency. So, the effective plasma frequency is tunable by changing the incident angle of EM wave. Also, variations of the incident angle leads to variations in reflected and transmitted frequency without changing the structure of the PPCs. Results show that group velocity varies with variation of the incident angle. So, by changing the incident angle of EM wave, the information transfer rate will be controllable. It is a success that we have the PPC tunable by external force that works in a frequencies range lower than plasma frequency. Also, the width and the refractive index of periodic structure have a significant effect on the mentioned properties of the PPC. The comparison of ternary PPCs with binary PPCs shows that in the same conditions, the number of bands in ternary PPCs is rather higher than in binary PPCs.

The flexibility of the ternary PPCs in comparison to binary PPCs leads to designing structures with better applications, such as omnidirectional antennas, omnidirectional mirrors, *etc*.

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