J. Plasma Physics (2014), *vol.* 80, *part* 4, *pp.* 581–592. © Cambridge University Press 2014
doi:10.1017/S0022377814000105

Magnetized plasma photonic crystals band gap

Elahe Ataei, Mehdi Sharifian† and Najmeh Zare Bidoki

Atomic & Molecular Group, Physics Department, Faculty of Science, Yazd University, Yazd 891995-741, Iran

(Received Received 29 December 2013; revised 10 February 2014; accepted 21 February 2014; first published online 9 April 2014)

In this paper, the effect of the magnetic field on one-dimensional plasma photonic crystal band gaps is studied. The one-dimensional fourfold plasma photonic crystal is applied that contains four periodic layers of different materials, namely plasma$_1$–MgF_2–plasma$_2$–glass in one unit cell. Based on the principle of Kronig–Penney's model, dispersion relation for such a structure is obtained. The equations for effective dielectric functions of these two modes are theoretically deduced, and dispersion relations for transverse electric (TE) and transverse magnetic (TM) waves are calculated. At first, the main band gap width increases by applying the exterior magnetic field. Subsequently, the frequency region of this main band gap transfers completely toward higher frequencies. There is a particular upper limit for the magnitude of the magnetic field above which increasing the exterior magnetic field strength doesn't have any significant influence on the dispersion function behavior. (With an increase in incident angle up to $\theta_1 = 66^\circ$, the width of photonic band gap (PBG) changes for both TM/TE polarization.) With an increase in incident angle up to $\theta_1 = 66^\circ$, the width of PBG decreases for TM polarization and the width of PBG increases for TE polarization, but it increases with further increasing of the incident angle from $\theta_1 = 66^\circ$ to 89° for both TE- and TM-polarizations. Also, it has been observed that the width of the photonic band gaps changes rapidly by relative difference of the two-plasma frequency. Results show the existence of several photonic band gaps that their frequency and dispersion magnitude can be controlled by the exterior magnetic field, incident angle, and two plasma frequencies. The result of this research would provide theoretical instructions for designing filters, microcavities, fibers, etc.

1. Introduction

Since the pioneering works of Yablonovitch (Yablonovitch 1987) and John (John 1987) on photonic crystals (PCs) field, many new inquisitive ideas have been extended. PCs are composed of periodic dielectric or metal–dielectric structures that affect the propagation of the electromagnetic (EM) waves. In the modern age of nanotechnology, the PCs or photonic band gap materials (PBGMs) have gained archival interest during the past decade. Now-a-days opening at random at any page of scientific or technical journals, even a magazine, one is likely to encounter phrases like 'photonic band gap materials' (John 1987; Yablonovitch 1987; Sakoda 2005).

These artificial dielectric materials are arranged periodically to show intervals of frequencies in which EM waves cannot be propagated. Such intervals of frequencies are called photonic band gaps (PBGs). These PBGs are produced due to a strong

† Email address for correspondence: mehdi.sharifian@yazd.ac.ir

https://doi.org/10.1017/S0022377814000105 Published online by Cambridge University Press

periodic variation in the dielectric constant or refractive index of different materials. The actual width of this band gap depends on the geometry, feature size, spacing, and nature of material that makes the crystal. The interest in the PBGMs arises due to the possible applications of such materials in several scientific and technical areas such as filters, waveguides, optical switches, cavities, design of more efficient layers, etc. It has been proven that a PBG could be formed as a result of the interference of Bragg scattering in a periodical dielectric structure. In a conventional PC, such a Bragg gap depends strongly on the details of the interference process. It is well known that the incident angle of an EM wave will influence the interference process within a PC. As the incident EM wave changes from normal to oblique incident, the Bragg gap will shift accordingly. The interference process is also sensitive to the polarization (transverse electric (TE) wave or transverse magnetic (TM) wave) of the incident wave, leading to a polarization-dependent gap. For example, at a certain incident angle, there is a Bragg gap for a TE wave but not for a TM wave. How to realize an omnidirectional gap based on a one-dimensional (1D) PC has attracted great interest due to its applications such as in perfect reflectors at all angles (Jiang et al. 2003). Several research works have been done other than 1D, two-dimensional (2D), and three-dimensional (3D) PBGMs consisting of positive and frequency-independent dielectrics because the problems due to absorption may be neglected (Scalora et al. 1997; Zheng et al. 2006). Recent studies (Yeh 1988; Bendickson et al. 1996) suggest that 1D periodic media are attractive candidates for this purpose. 1D periodic media can be fabricated more easily than 3D systems. They provide easy, cheap, and effective alternative possibility to improve the performance of various devices. 1D periodic media show enormous promise for band gap engineering and related applications.

Plasma photonic crystal (PPC) is a composite structure with a periodic arrangement of microplasma layer and dielectric material or microplasma layer with a periodic distribution density, which has particular properties other than conventional PCs composed of dielectrics or metals. PPCs represent a new kind of tunable PCs, which can act as an excellent tool to manipulate EM wave propagation, leading to many interesting phenomena as well as important applications. Moreover, by replacing solid material with plasma, two important features are added to the usual PC: first, time-varying controllability, and second, a strong dispersion around the plasma electron density. These facts will lead to EM waves ranging from microwaves to THz waves, according to the scale and electron density of such plasma (Sakai et al. 2007). Plasma is a kind of dispersive medium with its equivalent refractive index related to the frequency of an incident EM wave. Plasma is combined with dielectric material to form PPCs, of which the dispersion or the transmission properties have been studied. The technological applications of PPCs are now developing widely, as for example, in plasma lens (Goncharov et al. 1993), plasma antenna (Dwyer et al. 1984), plasma stealth aircraft (Vidmar 1990; Tang et al. 2003; Guo and Wang 2005), etc. PPC is a 1D, 2D, and 3D periodic structure of specially and dynamically controlled microplasma that plays a significant role in changing the refraction of EM waves. Such as, the concept of PPCs was first proposed by Hojo and Mase (2004) and subsequently, they discussed the dispersion of EM wave propagating in 1D PPCs using a method analogous to the solution of Kroning–Penny's problem in quantum mechanics and showed that the dispersion relation becomes band gap structure with frequency gap, and a cut-off frequency exists. Fukaya and Tominaga (2004) examined the propagation of EM waves in periodic multi-layers. Naumov and Zheltikov (2001) showed that multicomponent (foursome) 1D plasma photonic band

https://doi.org/10.1017/S0022377814000105 Published online by Cambridge University Press

gap (PPBG) structures provide additional degree of freedom in dispersion control compared with binary 1D PBG structure. Both Sakai et al. (Sakai et al. 2005) and Liu et al. (2009) have investigated the plasma collision effect on the EM waves propagating in PPC. The former studied 2D PPC and the latter studied 1D PPC. Shiveshwari and Mahto (2006) discussed the PBG structure of the 1D PPC in terms of plasma density, plasma width, and number of unit cells. Liu et al. (2005; 2006) adopted the finite-difference time-domain (FDTD) method to study the propagation process with Gaussian pulses passing in the unmagnetized and magnetized PPCs. In time domain, the reflection and transmission on the electric field of EM waves have been investigated. In frequency domain, the reflection and transmission coefficients of the pulses through the two kinds of crystals have been computed. Guo (Bin 2009; Guo 2009) studied the dispersion relation of obliquely incident EM waves in 1D PPC and discussed the dependences of dispersion relation on incident angle, collision frequency, plasma-filling factor, and dielectric constant of dielectric. Yin et al. (2009) investigated theoretically and numerically the band gap characteristics of a 1D PPC composed of plasma layers of different densities. Zhang et al. (2009) studied the transmission properties of a normal incident Gaussian impulse in a 1D magnetized PPC (1D MPPC) by the FDTD method. Recently, Qi et al. (2010) focused on the properties of the transmission and the dispersion relation influenced by the external magnetic field, etc. Recently, the dispersion characteristic of a ternary plasma PBG structure has been studied theoretically. None of them was introduced as a ternary 1D PPC until, Prasad et al. (2010; 2011; 2012] investigated the modal propagation characteristics of unmagnetized ternary 1D PPC structures and showed that the plasma frequency, plasma width, dielectric constant, incident angles, and collisions have marked influence on the band gap, group velocity, effective phase index, and group index. They have also shown that ternary 1D PPC structures provide an additional degree of freedom to control the dispersion characteristic compared to binary 1D PPC structures. The PBG in a larger frequency range could be modulated by changing the structure parameters of the plasma layer. Zhang et al. (2012) studied the properties of PBGs and dispersion relations of 1D MPPCs composed of dielectric and magnetized plasma layers, with arbitrary magnetic declination theoretically investigated for TM wave propagating in 1D MPPCs based on TMM.

For 2D and 3D cases, Qi (2012) investigated the dispersion for 2D MPPCs by planewave expansion (PWE) method and found that the PBGs can be tuned by the parameters of magnetized plasma. Zhang et al. (Hai-Feng et al. 2011; Zhang et al. 2011) studied the transmission and defect mode properties of 2D PPCs for TM wave by FDTD method, and pointed out that the PBGs and defect mode can be tuned by plasma frequency, host dielectric constant, and filling factor, respectively. Fu et al. (2013) analyzed the dispersion relation of magnetic plasma–metal PCs based on FDTD method, and found that the positions of the flat bands, cut-off frequency, and PBGs can be controlled by the external magnetic field. On the other hand, Zhang et al. (2012) and Qi and Zhang (2011) arranged plasma periodically by the external magnetic field to form a new kind of 2D and 1D MPPCs, which are only composed of the plasma, and proclaimed that the PBGs also can be tuned by the external magnetic field. Zhang et al. (2012; 2013a, c) proposed the properties of PBGs for 3D non-magnetized PPCs with diamond and simple-cubic (sc) lattices. The same research group also investigated the dispersive properties of 3D MPPCs (Zhang et al. 2013b, d). As mentioned in their works (Zhang et al. 2012; 2013d), 3D PPCs with sc lattices will suffer from high-symmetry lattices, and dielectric constant of dielectric must be sufficiently large so that the resonant scattering of EM waves is prominent enough

https://doi.org/10.1017/S0022377814000105 Published online by Cambridge University Press

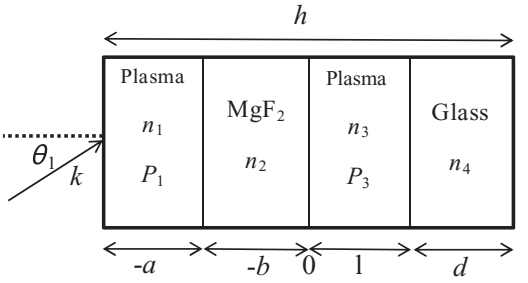


FIGURE 1. Schematic representation of the fourfold 1D plasma photonic crystal. Here$h = a + b + l + d$ is the unit cell width.

to open a band gap (Li et al. 1998). Unfortunately, technological difficulties can be found in fabricating the 3D PPCs to obtain the complete PBGs with large dielectric constant of dielectric. Therefore, if we want to achieve complete PBGs in 3D MPPCs with high symmetry lattices, we have to break the high symmetry (Malkova et al. 2003) and use anisotropic dielectric to realize the PCs (Li et al. 1998).

All the works mentioned above focused on the PBG characteristics of the binary 1D PPC and ternary 1D PPC which are composed of alternating layers of plasma and one or two layers of dielectric materials. In this paper we have looked into a new development of PPCs and chosen fourfold 1D PPC having periodic layers of four different materials, namely: $plasma_1$–MgF_2–$plasma_2$–glass in one unit cell. We have obtained dispersion relation for such a structure on the principle of Kronig–Penney's model. The formula of the effective refraction index of plasma layers, exterior magnetic field on dielectric function of plasma layers, and dispersion equation of TE and TM polarizations are deduced. It has been studied the effect of many items such as PPC structure, magnetic field, incidence angle and relative difference of two normalized plasma frequencies, on PPC band gaps.

2. Basic equations

A theoretical analysis has been made for propagation of the EM waves through a fourfold 1D PPC as shown in Fig. 1. Let us consider that an obliquely incident EM wave is propagating in the *yz* plane. Wave equation for EM waves propagating in 1D is given by

$$\frac{d^2E(z)}{dz^2} + \left[\left(\frac{\omega n}{c}\right)^2 - \beta^2\right] E(z) = 0, \tag{1}$$

where β is the propagation constant and its value is given by $\beta = \frac{n_i\omega}{c}\sin\theta_i$; $(i = 1, 2, 3, 4)$, ω is the frequency of the EM waves propagating in the crystals, c is the light velocity in the free space, and n is the refractive index that is given as (Bin et al. 2013)

$$n(z) = \begin{cases} n_1 & -(a+b) < z < -b; \quad \omega > \omega_{p_1} \\ n_2 = (\varepsilon_2)^{1/2} & -b < z < 0 \\ n_3 & 0 < z < l; \quad \omega > \omega_{p_3} \\ n_4 = (\varepsilon_4)^{1/2} & l < z < l + d \end{cases}, \tag{2a}$$

https://doi.org/10.1017/S0022377814000105 Published online by Cambridge University Press

$$\vec{k} \parallel \vec{B} \text{ Faradey effect} \rightarrow \begin{cases} n_1 = \left(1 - \dfrac{\omega_{p_1}^2}{\omega(\omega - \omega_B)}\right)^{1/2}, & \text{(TE polarization)} \\ n_3 = \left(1 - \dfrac{\omega_{p_3}^2}{\omega(\omega - \omega_B)}\right)^{1/2}, & \text{(TE polarization)} \end{cases}, \tag{2b}$$

$$\vec{k}^{\perp}\vec{B} \rightarrow \text{Voigt effect} \rightarrow \begin{cases} n_1 = \left(1 - \dfrac{\omega_{p_1}^2\left(\omega^2 - \omega_{p_1}^2\right)}{\omega^2\left(\omega^2 - \omega_B^2 - \omega_{p_1}^2\right)}\right)^{1/2}, & \text{(TM polarization)} \\ n_3 = \left(1 - \dfrac{\omega_{p_3}^2\left(\omega^2 - \omega_{p_3}^2\right)}{\omega^2\left(\omega^2 - \omega_B^2 - \omega_{p_3}^2\right)}\right)^{1/2}, & \text{(TM polarization)} \end{cases}, \tag{2c}$$

with $n(z) = n(z+h)$. Here $\omega_B = eB/m_e$ is the electron gyro frequency (e is the electron charge and m_e is the electron mass), n_1, $n_2 = 1.38$ and n_3, $n_4 = 1.5$ are the four refractive indices of the materials (plasma$_1$ (n_1), MgF_2 (n_2), plasma$_2$ (n_3), and glass (n_4)) with thickness a, b, l, and d, respectively, ε_2 and ε_4 are dielectric constants of the second and fourth layers, respectively, and $h = a + b + l + d$ is the period of the lattice.

Also,$\omega_{p_1} = (\frac{n_{p_1}e^2}{m\varepsilon_0})^{1/2}$ and $\omega_{p_3} = (\frac{n_{p_3}e^2}{m\varepsilon_0})^{1/2}$ are the electron plasma frequencies of the first and third layers, respectively. n_{p_1} and n_{p3} are the electron plasma densities of the first and third layers, respectively. For four different regions, (1) can be expressed as

$$\begin{cases} \dfrac{d^2E(z)}{dz^2} + \left[\left(\dfrac{\omega n_1}{c}\right)^2 - \beta^2\right] E(z) = 0 & -(a+b) < z < -b \\ \dfrac{d^2E(z)}{dz^2} + \left[\left(\dfrac{\omega n_2}{c}\right)^2 - \beta^2\right] E(z) = 0 & -b < z < 0 \\ \dfrac{d^2E(z)}{dz^2} + \left[\left(\dfrac{\omega n_3}{c}\right)^2 - \beta^2\right] E(z) = 0 & 0 < z < l \\ \dfrac{d^2E(z)}{dz^2} + \left[\left(\dfrac{\omega n_4}{c}\right)^2 - \beta^2\right] E(z) = 0 & l < z < l + d \end{cases}. \tag{3}$$

Its solutions for four alternate layers can be written as

$$E(z) = \begin{cases} a_n e^{ik_1 z} + b_n e^{-ik_1 z} & -(a+b) < z < -b \\ c_n e^{ik_2 z} + d_n e^{-ik_2 z} & -b < z < 0 \\ e_n e^{ik_3 z} + f_n e^{-ik_3 z} & 0 < z < l \\ g_n e^{ik_4 z} + h_n e^{-ik_4 z} & l < z < l + d \end{cases}, \tag{4}$$

where a_n, b_n, c_n, d_n, e_n, f_n, g_n, and h_n are unknown coefficients and $k_i = [(\frac{\omega}{c})^2 n_i - \beta^2]^{1/2} = \frac{\omega n_i}{c}\cos\theta_i$; $(i = 1, 2, 3, 4)$ are the wave-vectors in four regions. $\theta_1, \theta_2, \theta_3, \theta_4$ are ray angles in each layer and they are related with the incident angle

https://doi.org/10.1017/S0022377814000105 Published online by Cambridge University Press

θ_1 by the following relation:

$$\theta_2 = \cos^{-1}\sqrt{1-\left(\frac{n_1}{n_2}\right)^2\sin^2\theta_1},$$
$$\theta_3 = \cos^{-1}\sqrt{1-\left(\frac{n_1}{n_3}\right)^2\sin^2\theta_1}, \quad (5)$$
$$\theta_4 = \cos^{-1}\sqrt{1-\left(\frac{n_1}{n_4}\right)^2\sin^2\theta_1}.$$

First the continuity conditions of the electric field, $E(z)$, and its derivatives, $dE(z)/dz$, at the boundaries, viz. $z = 0$, $-(a+b)$, $-b$, l, and $(l+d)$ have been imposed. The following matrix equation can be obtained (Prasad et al. 2010):

$$\begin{bmatrix} a_{n-1} \\ b_{n-1} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} a_n \\ b_n \end{bmatrix}, \quad (6)$$

where A, B, C, and D are the matrix elements for the unit cell translation matrix that relates the complex amplitude of the incident wave a_{n-1} and the reflected planewave b_{n-1} in one layer of a unit cell to those of the equivalent layer in the next unit cell. Using Bloch's theorem, $E_k(z,t) = E_k(z)\,e^{-i\omega t}e^{ikz}$, where Bloch function $E_k(z+h) = E_k(z)$ and after simplification, with $\omega > \omega_{p_1} > \omega_{p_3}$, the dispersion relation for the 1D fourfold PPC may be written as

$$\begin{aligned} K(\omega) = \frac{1}{h}[&\cos(ak_1)\cos(bk_2)\cos(lk_3)\cos(dk_4) - \frac{1}{2}\left(\frac{\gamma_1}{\gamma_2}+\frac{\gamma_2}{\gamma_1}\right) \\ &\times \cos(lk_3)\cos(dk_4)\sin(ak_1)\sin(lk_3)\cos(dk_4) - \frac{1}{2}\left(\frac{\gamma_1}{\gamma_3}+\frac{\gamma_3}{\gamma_1}\right) \\ &\times \cos(bk_2)\cos(dk_4)\sin(ak_1)\sin(lk_3) - \frac{1}{2}\left(\frac{\gamma_2}{\gamma_3}+\frac{\gamma_3}{\gamma_2}\right) \\ &\times \cos(ak_1)\cos(dk_4)\sin(bk_2)\sin(lk_3) - \frac{1}{2}\left(\frac{\gamma_1}{\gamma_4}+\frac{\gamma_4}{\gamma_1}\right) \\ &\times \cos(ak_1)\cos(lk_3)\sin(bk_2)\sin(dk_4) - \frac{1}{2}\left(\frac{\gamma_3}{\gamma_4}+\frac{\gamma_4}{\gamma_3}\right) \\ &\times \cos(ak_1)\cos(bk_2)\sin(lk_3)\sin(dk_4) + \frac{1}{2}\left(\frac{\gamma_1\gamma_3}{\gamma_2\gamma_4}+\frac{\gamma_2\gamma_4}{\gamma_1\gamma_3}\right) \\ &\times \sin(ak_1)\sin(bk_2)\sin(lk_3)\sin(dk_4)], \end{aligned}$$

where $\gamma_i = k_i$; $(i = 1, 2, 3, 4)$ for TE polarizations, and $\gamma_i = n_i^2 k_i$; $(i = 1, 2, 3, 4)$ for TM polarizations.

3. Results and discussion

Using (7), we have computed the band structure in the form of dispersion curve for the 1D fourfold PPC containing four periodic layers of different materials, namely plasma$_1$–MgF_2–plasma$_2$–glass in one unit cell as shown in Fig. 1. Here we have chosen plasma$_1$ of width a with refractive index n_1; MgF_2 of width b having refractive index $n_2 = 1.38$; plasma$_2$ of width l with refractive index n_3, and glass of width d having refractive index $n_4 = 1.5$. The total number of unit cell is $N = 5$. The

https://doi.org/10.1017/S0022377814000105 Published online by Cambridge University Press

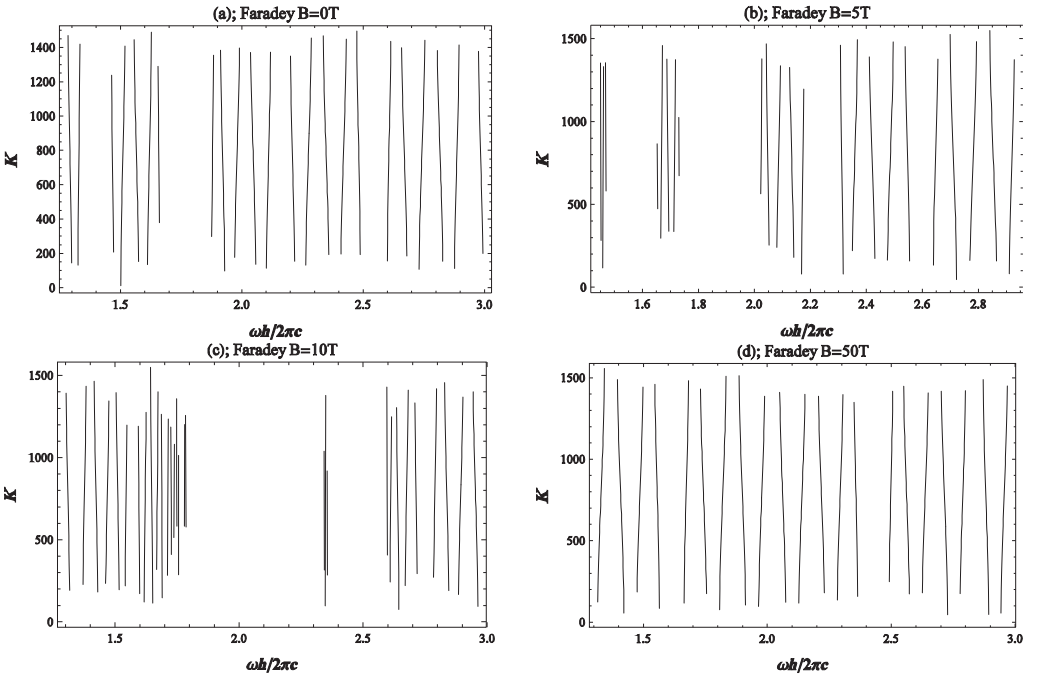


FIGURE 2. Dispersion curves for diameter $a = b = l = d = 500\,\mu$m and normalized plasma frequencies $P_1 = 2$ and $P_3 = 1$ for various applied Faradey external magnetic field intensities $B = 0, 5, 10, 50T$ (Tesla).

normalized plasma frequencies are $p_1 = \frac{\omega_{p1}a}{c} = 2$ and $p_3 = \frac{\omega_{p3}l}{c} = 1$, respectively. The dispersion relation of the proposed structure is in the form of normalized frequency ($V = \omega h/2\pi c$) versus wave-vector. As expected, PBGs are observed in all considered cases. These gaps are intrinsic consequence of periodicity of the layers and the gap frequency is tied with size of the unit cell (Prasad et al. 2010).

The dispersion relation of the proposed structure in the form of normalized frequency ($V = \omega h/2\pi c$) versus wave-vector for different values of the Faradey and Voigt exterior magnetic field ($B = 0,\ 5,\ 10,\ 50T$) are shown in Fig. 2. In this study, we increase the exterior magnetic field by fixing the normalized plasma frequencies and the layers' diameters. By comparing Figs. 2(a) and 3(a) with 2(b) and 3(b), it can be observed that when an exterior magnetic field is applied on the plasma, the main (broad) band gap width expands more compared to when there is not any exterior magnetic field ($B = 0$). In Figs. 2(c) and 3(c), it could be seen that increasing of the exterior magnetic field results in the expansion of the main band gap and compression of the secondary band gaps between and around the two main band gaps. Furthermore, it's been observed that the frequency region of the main band gaps has been completely transferred toward the higher frequencies. Figures 2(d) and 3(d), in which the strongest magnetic field ($B = 50T$) has been applied on the plasma, depicts the disappearance of the main band gaps. Also, as was expected from (2), further increasing of the magnetic field from an upper limit ($|(\frac{\omega_{P3}^2}{\omega(\omega-\omega_B)}| \ll 1$) does not have effect on the refractive index of the plasma (since the plasma refractive index will tend to the value $n = 1$), or on the dispersion relation of the structure.

https://doi.org/10.1017/S0022377814000105 Published online by Cambridge University Press

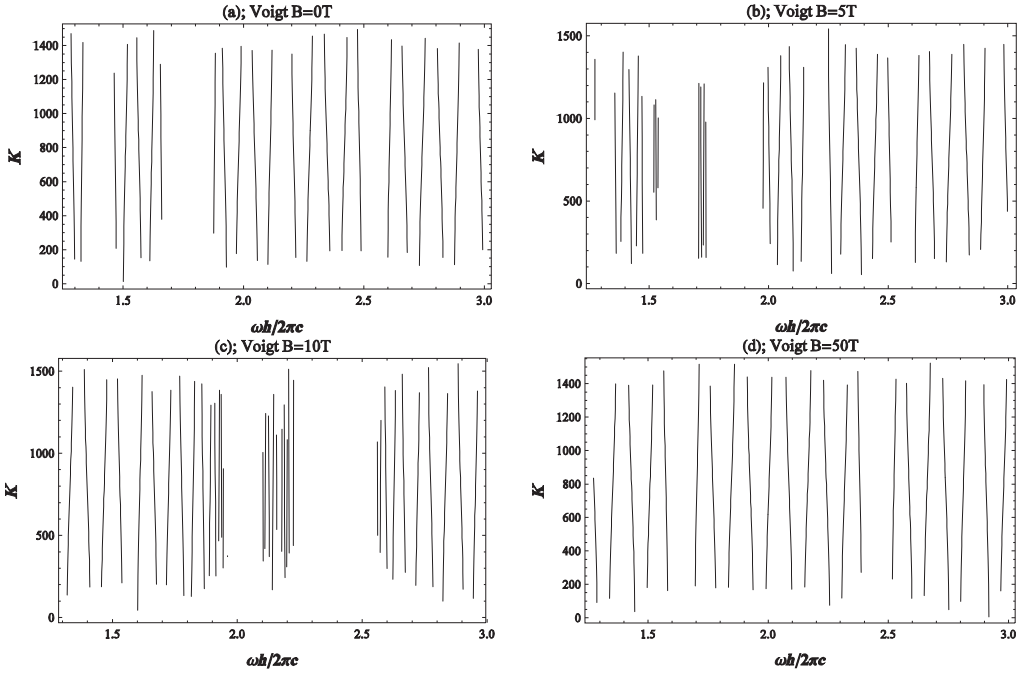


FIGURE 3. Dispersion curves for diameter $a = b = l = d = 500\,\mu$m and normalized plasma frequencies $P_1 = 2$ and $P_3 = 1$ for various applied Voigt external magnetic field intensities $B = 0, 5, 10, 50T$ (Tesla).

Therefore, for very strong magnetic field, the band gap widths will be independent of the magnetic field.

The influence of the incident angle ($\theta_1 = 15°, 45°, 66°, 89°$) on the band gaps for the TM and TE polarizations has been depicted in Figs. 4(a) and (b), respectively. It is could be found that the main PBG shifts upward in frequency for both TE and TM polarizations when the incident angle increases.

For the TE polarization, as shown in Fig. 4(a), the main PBG is obviously enlarged when the incident angle increases. Also, the dispersion is increased when the angle of incidence is increased, but at $\theta_1 = 89°$ the PBG has been very large.

For TM polarization, the main PBG decreases by increasing of the incident angle up to $\theta_1 = 66°$, but after that, by further increasing of the incident angle, the main PBG increases. As for the TM polarization, in Fig. 4(b) it can be seen that the dependency of the PBG on the incident angle, unlike the TE polarization is not monotonic. In other words, it increases and decreases by increasing of the incident angle.

In Fig. 5, normalized plasma frequency of the second plasma layer has been fixed ($P_3 = 1$), but the first normalized frequency increased from $P_1 = 2$ to 4. It could be seen that the width of the band gap increases with the increasing of the plasma frequency of the first layer. In this figure, also by keeping the first plasma frequency at constant value ($P_1 = 4$), the second plasma frequency has been changed from $P_3 = 1$ to 3.

Finally, it can be seen that band gap width increases by increasing the frequency difference between the plasma frequencies of the two layers.

https://doi.org/10.1017/S0022377814000105 Published online by Cambridge University Press

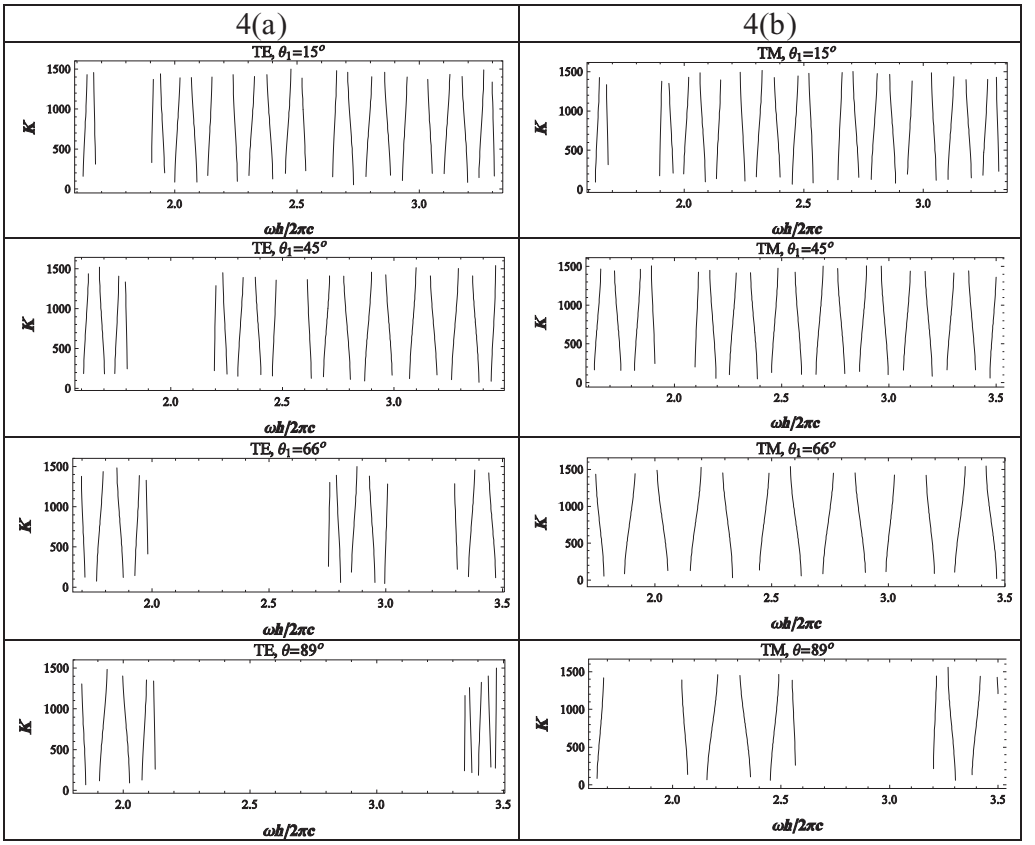


FIGURE 4. Dispersion curves for diameter $a = b = l = d = 500\,\mu$m and normalized plasma frequencies $P_1 = 2$ and $P_3 = 1$ for incident angle ($\theta_1 = 15°, 45°, 66°, 89°$): (a) TE polarization, (b) TM polarization.

4. Conclusion

Using Maxwell equations based on Kroning-Penny's model and the matrix technique, it has been studied the transition of the dispersion relationship in the four layers of magnetized plasma photonic crystal in the single cell and then drawn and concluded the dispersion curves. By applying the exterior magnetic field, the main band gap width increases and the frequency region of the main band gap completely shifts toward the higher frequencies. There is an upper limit for increasing of the magnetic field after which the magnetic field does not have significant effect on the dispersion function behavior and causes the disappearance of the PPC broad band gaps which are created by the exterior magnetic field in lower value ($B < 50T$).

As for TE polarization, the width of the PBG could be expanded by increasing of the incident angle. But, for TM polarization, the width of the PBG is decreased by increasing of the incident angle up to $\theta_1 = 66°$ and increased with further increasing of the incident angle from $\theta_1 = 66°$ to 89°.

Also, it has been concluded that the width of the band gap increases with increasing of the difference between the normalized plasma frequencies of two plasma layers.

https://doi.org/10.1017/S0022377814000105 Published online by Cambridge University Press

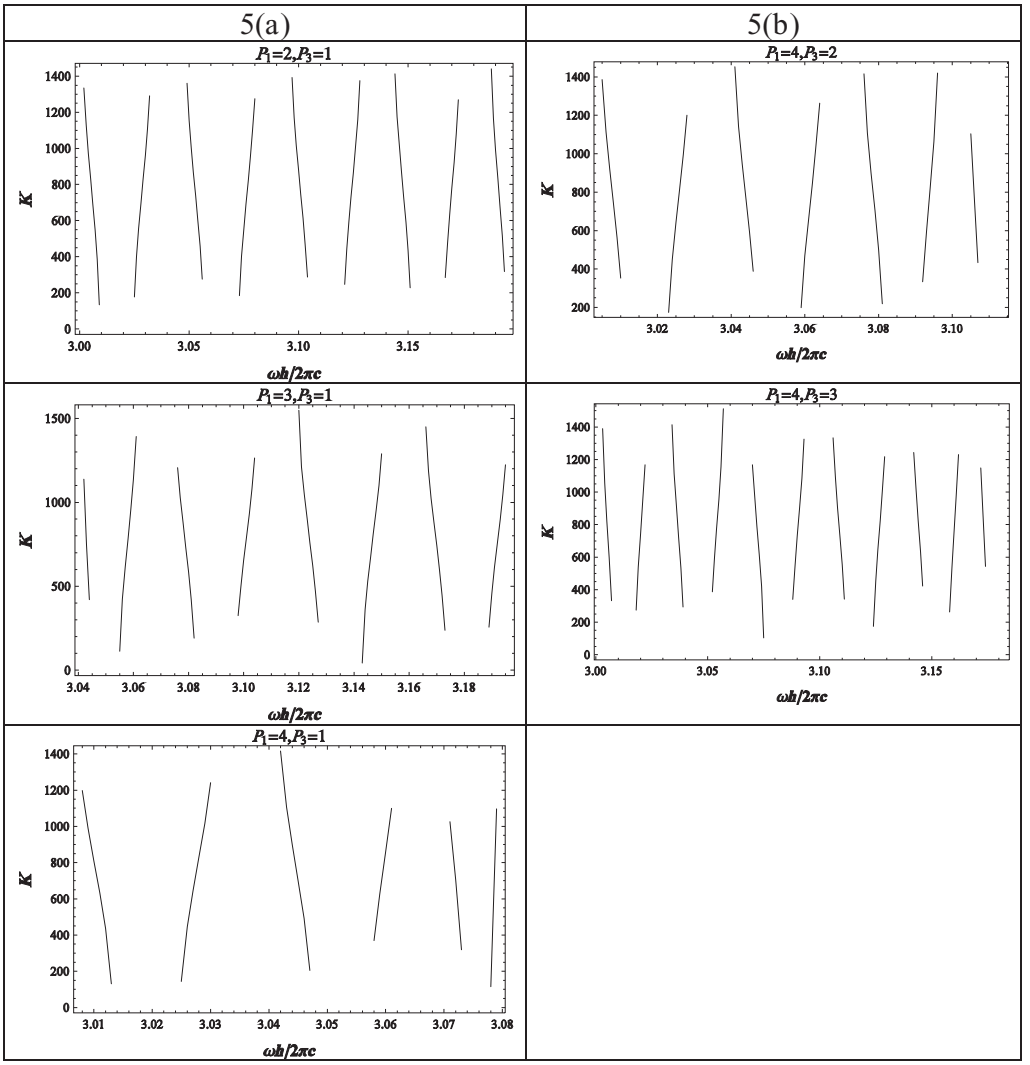


FIGURE 5. Dispersion curves for thickness of $a = b = l = d = 500\mu$ m where plasma frequencies are $P_1 = 2, 3, 4$ and $P_3 = 1$ (3a); $P_1 = 4$ and $P_3 = 1, 2, 3$ (3b).

REFERENCES

Bendickson, J. M., Dowling, J. P. and Scalora, M. 1996 Analytic expressions for the electromagnetic mode density in finite, one-dimensional, photonic band-gap structures. *Phys. Rev.* E **53**(4), 4107.

Bin, G. 2009 Transfer matrix for obliquely incident electromagnetic waves propagating in one dimension plasma photonic crystals. *Plasma Sci. Technol.* **11**(1), 18.

Bin, G., Li, P. and Xiaoming, Q. 2013 Tunability of one-dimensional plasma photonic crystals with an external magnetic field. *Plasma Sci. Technol.* **15**(7), 609.

Dwyer, T. J. et al. 1984 On the feasibility of using an atmospheric discharge plasma as RF antenna. *IEEE Trans. Antenna Propag.* **AP-32**(2), 141–146.

Fu, T. et al. 2013 Dispersion properties of a 2D magnetized plasma metallic photonic crystal. *Phys. Plasmas* **20**, 023109.

Fukaya, T. and Tominaga, J. 2004 Slab lens with restrained light propagation in periodic multilayer. *JOSA* B **21**(7), 1280–1288.

Goncharov, A. A. et al. 1993 High-current plasma lens. *IEEE Trans. Plasma Sci.* **21**(5), 573–577.

https://doi.org/10.1017/S0022377814000105 Published online by Cambridge University Press

Guo, B. 2009 Photonic band gap structures of obliquely incident electromagnetic wave propagation in a one-dimension absorptive plasma photonic crystal. *Phys. Plasmas* **16**(4), 043 508.

Guo, B. and Wang, X. 2005 Power absorption of high-frequency electromagnetic waves in a partially ionized magnetized plasma. *Phys. Plasmas* **12**(8), 084506-4.

Hai-Feng, Z., Shao-Bin, L. and Xiang-Kun, K. 2011 Defect mode properties of two-dimensional unmagnetized plasma photonic crystals with line-defect under transverse magnetic mode. *Acta Phys. Sin.* **60**(2), 025215.

Hojo, H. and Mase, A. 2004 Dispersion relation of electromagnetic waves in one-dimensional plasma photonic crystals. *J. Plasma Fusion Res.*, **80**(2), 89–90.

Jiang, H. et al. 2003 Omnidirectional gap and defect mode of one-dimensional photonic crystals containing negative-index materials. *Appl. Phys. Lett.* **83**(26), 5386–5388.

John, S. 1987 Strong localization of photons in certain disordered dielectric superlattices. *Phys. Rev. Lett.* **58**(23), 2486–2489.

Li, Z.-Y., Gu, B.-Y. and Yang, G.-Z. 1998 Large absolute band gap in 2D anisotropic photonic crystals. *Phys. Rev. Lett.* **81**(12), 2574.

Li, Z.-Y., Wang, J. and Gu, B.-Y. 1998 Creation of partial band gaps in anisotropic photonic-band-gap structures. *Phys. Rev.* B **58**(7), 3721.

Liu, S., Hong, W. and Yuan, N. 2006 Finite-difference time-domain analysis of unmagnetized plasma photonic crystals. *Int. J. Infrared Millim. Waves* **27**(3), 403–423.

Liu, S., Zhong, S. and Liu, S. 2009 A study of properties of the photonic band gap of unmagnetized plasma photonic crystal. *Plasma Sci. Technol.* **11**(1), 14.

Liu S.-B., Zhu C.-X. and Yuan N.-C. 2005 FDTD simulation for plasma photonic crystals. *Acta Phys. Sin.* **54**(6), 2804–2808.

Malkova, N. et al. 2003 Symmetrical analysis of complex two-dimensional hexagonal photonic crystals. *Phys. Rev.* B **67**(12), 125203.

Naumov, A. and Zheltikov, A. 2001 Ternary one-dimensional photonic band-gap structures: dispersion relation, extended phase-matching abilities, and attosecond outlook. *Laser Phys.* **11**(7), 879–884.

Prasad, S., Singh, V. and Singh A. K. 2010 Modal propagation characteristics of EM waves in ternary one-dimensional plasma photonic crystals. *Optik – Int. J. Light Electron. Opt.* **121**(16), 1520–1528.

Prasad, S., Singh, V. and Singh, A. K. 2011 A comparative study of dispersion relation of EM waves in ternary one-dimensional plasma photonic crystals having two different structures. *Optik – Int. J. Light Electron. Opt.* **122**(14), 1279–1283.

Prasad, S., Singh, V. and Singh, A. K. 2012 Properties of ternary one dimensional plasma photomic crystals for an obliquely incident electromagnetic wave considering the effect of collisions in plasma layers. *Plasma Sci. Technol.* **14**(12), 1084.

Qi, L. 2012 Photonic band structures of two-dimensional magnetized plasma photonic crystals. *J. Appl. Phys.* **111**(7), 073301-073301-8.

Qi, L. and Zhang, X. 2011 Band gap characteristics of plasma with periodically varying external magnetic field. *Solid State Commun.* **151**(23), 1838–1841.

Qi, L. et al. 2010 Properties of obliquely incident electromagnetic wave in one-dimensional magnetized plasma photonic crystals. *Phys. Plasmas* **17**(4), p. 042501-8.

Sakai, O., Sakaguchi, T. and Tachibana, K. 2005 Verification of a plasma photonic crystal for microwaves of millimeter wavelength range using two-dimensional array of columnar microplasmas. *Appl. Phys. Lett.* **87**(24), 241505-241505-3.

Sakai, O., Sakaguchi, T. and Tachibana, K. 2007 Photonic bands in two-dimensional microplasma arrays. I. Theoretical derivation of band structures of electromagnetic waves. *J. Appl. Phys.* **101**(7), 073304-9.

Sakoda, K. 2005 *Optical Properties of Photonic Crystal*. New York, NY: Springer.

Scalora, M. et al. 1997 Pulsed second-harmonic generation in nonlinear, one-dimensional, periodic structures. *Phys. Rev.* A **56**(4), 3166.

Shiveshwari, L. and Mahto, P. 2006 Photonic band gap effect in one-dimensional plasma dielectric photonic crystals. *Solid State Commun.* **138**(3), 160–164.

Tang, D. L., Sun, A. P., Qiu, X. M. and Chu P. K. 2003 Interaction of electromagnetic waves with a magnetized nonuniform plasma slab. *IEEE Trans. Plasma Sci.* **31**(3), 405–410.

https://doi.org/10.1017/S0022377814000105 Published online by Cambridge University Press

Vidmar, R. J. 1990 On the use of atmospheric pressure plasmas as electromagnetic reflectors and absorbers. *IEEE Trans. Plasma Sci.* **18**(4), 733–741.

Yablonovitch, E. 1987 Inhibited spontaneous emission in solid-state physics and electronics. *Phys. Rev. Lett.* **58**(20), 2059–2062.

Yin, Y. et al. 2009 Bandgap characteristics of one-dimensional plasma photonic crystal. *Phys. Plasmas* **16**(10), 102103–102105.

Yeh, P. 1988 *Optical Waves in Layered Media*. Vol. 95. Wiley Online Library.

Zhang, H., Kong, X. and Liu, S. 2011 Analysis of the properties of tunable prohibited band gaps for two-dimensional unmagnetized plasma photonic crystals under TM mode. *Acta Phys. Sin.* **60**, 055209.

Zhang, H.-F., Liu, S.-B. and Kong, X.-K. 2012 Photonic band gaps in one-dimensional magnetized plasma photonic crystals with arbitrary magnetic declination. *Phys. Plasmas* **19**(12), 122103–13.

Zhang, H.-F., Liu, S.-B. and Kong, X.-K. 2013a Dispersion properties of three-dimensional plasma photonic crystals in diamond lattice arrangement. *J. Lightwave Technol.* **31**(11), 1694–1702.

Zhang, H.-F., Liu, S.-B. and Li, B.-X. 2013b The properties of photonic band gaps for three-dimensional tunable photonic crystals with simple-cubic lattices doped by magnetized plasma. *Opt. Laser Technol.* **50**, 93–102.

Zhang, H.-F., Ma, L. and Liu, S.-B. 2009 Study of periodic band gap structure of the magnetized plasma photonic crystals. *Optoelectron. Lett.* **5**(2), 112–116.

Zhang, H.-F. et al. 2012 Dispersion properties of two-dimensional plasma photonic crystals with periodically external magnetic field. *Solid State Commun.* **152**(14), 1221–1229.

Zhang, H.-F. et al. 2012 The characteristics of photonic band gaps for three-dimensional unmagnetized dielectric plasma photonic crystals with simple-cubic lattice. *Opt. Commun.* **288**, 82–90.

Zhang, H.-F. et al. 2013c The properties of photonic band gaps for three-dimensional plasma photonic crystals in a diamond structure. *Phys. Plasmas* **20**, 042110.

Zhang, H.-F. et al. 2013d Analysis of photonic band gap in dispersive properties of tunable three-dimensional photonic crystals doped by magnetized plasma. *Phys. Plasmas* **20**, 032118.

Zheng, Q., Fu, Y. and Yuan, N. 2006 Characteristics of planar PBG structures with a cover layer. *J. Electromagn. Waves Appl.* **20**(11), 1439–1453.

https://doi.org/10.1017/S0022377814000105 Published online by Cambridge University Press