Effect of a magnetic field on a two-dimensional metallic photonic crystal

Ali Hatef[1] and Mahi R. Singh[2]

[1]*Laser Processing and Plasmonics Laboratory, Engineering Physics Department, Ecole Polytechnique de Montreal, Montreal, Quebec, Canada H3C 3A7*

[2]*Department of Physics and Astronomy, University of Western Ontario, London, Ontario, Canada N6A 3K7*

(Received 17 January 2012; revised manuscript received 1 September 2012; published 26 October 2012)

We study the effect of a static magnetic field on the band structure of a two-dimensional metallic photonic crystal (MPC). The band structure of the MPC has been calculated using the transfer matrix method. It is found that the position of the photonic band gap and the band edges of the MPC depends on the polarization of the incident light and intensity of the applied magnetic field. In our calculations we consider linearly polarized light as well as right- and left-circularly polarized light. In the case of right-circularly polarized light it is found that as the intensity of the magnetic field increases the width of the band gap of the crystal decreases. At a certain magnetic field strength the band gap disappears altogether. In other words there is a transition from a metallic photonic band gap material to a transparent dielectric material. This is an interesting effect which is similar to the metal-insulator transition that occurs in semiconductors. On the other hand, for left-circularly and linear polarized light the band edges shift to the higher energy and the band gap increases in the presence of a magnetic field. This implies that the MPC switches from a transparent state to reflecting states due to the application of the magnetic field. This is an interesting effect which might be used to make photonic switches.

DOI: 10.1103/PhysRevA.86.043839 PACS number(s): 42.70.Qs, 78.66.Bz, 78.20.Bh, 78.20.Ls

I. INTRODUCTION

A distinctive feature of photonic crystals is the presence of one or more global photonic band gaps. It is known that a high dielectric contrast is required to have a complete photonic gap in dielectric photonic crystals [1]. These conditions have severely restricted the set of dielectrics that exhibit a photonic band gap. However, metals with energy-dependent dielectric constants are the best alternative to overcome this barrier [2,3]. These crystals, which are called metallic photonic crystals (MPCs) or metallodielectric photonic crystals, are more reflective over a broader range of frequencies than those made of dielectric or semiconductor materials. Photons also interact much more strongly with metals than with dielectrics. Hence these structures are more likely to possess a complete photonic band gap than their dielectric counterparts. The band gap in these crystals is due to the plasma screening effects and Bragg scattering. Therefore they are more useful for developing integrated photonic devices [4,5].

Much experimental and theoretical research has been done on two-dimensional (2D) MPCs because of their potential to control electronic and photonic resonances simultaneously. For example, Moroz [6] showed that small metal inclusions can have a dramatic effect on the photonic band structure of diamond and zinc-blende photonic crystals. Ustyantsev and co-workers [7] theoretically studied the effect of the dielectric background in 2D MPCs consisting of a square lattice of circular metallic rods embedded into a dielectric background. They showed that the band structures shift toward lower frequencies and become flatter when the background dielectric constant increases. However, there has been little work done to investigate tunable MPCs whose characteristics can be controlled by external factors. For example, Kee *et al.* [8] investigated the heliconic band structure of one-dimensional MPCs. They showed that the heliconic band structure can easily be controlled by an external static magnetic field. Lim *et al.* [9] studied the effects of liquid crystal infiltration on the photonic band gaps (PBGs) of 2D square and triangular lattices of metallic rods (tunable MPCs). The infiltration of liquid crystals into the square lattice enlarges the PBG that already exists in the air background and creates another higher-order PBG. Figotin *et al.* [10] showed how the electromagnetic spectrum of the photonic crystal can be altered over a wide range by an external quasistationary uniform magnetic and electric field.

Recently Wang *et al.* [11] demonstrated theoretically a different mechanism for creating a one-way waveguide where a magnetic field can lift the intrinsic degeneracy of photonic bands, create a band gap, and generate reflection-free one-way edge modes. They showed the existence of one-way electromagnetic modes in a waveguide formed between a semi-infinite photonic crystal structure and a semi-infinite metal region under a static magnetic field. Fu and co-workers [12], built a 2D square-lattice gyromagnetic photonic crystal from the magneto-optical material yttrium iron garnet and demonstrated its tunable electromagnetic properties by placing the photonic crystal in a tunable dc magnetic field and measuring the transmission spectra for microwaves.

In this paper we study the effect of a magnetic field on the band structure of a two-dimensional metallic photonic crystal. We consider 2D MPCs made from rectangular metallic pillars arranged periodically in a 2D plane, where air is taken as the background medium. The advantage of choosing two metals lies in the fact that one can easily control the size and location of the crystal's band gap by manipulating the plasma frequencies of two metals rather than one. This structure has another advantage in that one can obtain analytical expressions for the band structure and transmission coefficient. We consider a MPC consisting of aluminum (Al) with zinc (Zn) in an air background [13]. The band structures for linearly polarized (LP), right-circularly polarized (RCP), and left-circularly polarized (LCP) light are calculated. We also calculate the transmission coefficient for RCP light.

It is found that the positions of the photonic band gap and the band edges of the MPC depend on the polarization of the incident light and the intensity of the applied magnetic field. For example, for LP and LCP light the band gap increases with increase of the magnetic field. This is because the refractive index of metals depends on the magnetic field. The band edges shift to higher energy due to the magnetic field. This implies that in the presence of a magnetic field the crystal switches from a transparent state to reflecting states, and vice versa. This effect can be used to make photonic switches. On the other hand, for RCP light it is found that as the intensity of magnetic field is increased the width of the band gap decreases. At a certain magnetic field strength (called the critical value) the band gap disappears altogether. In other words, there is a transition from a 2D MPC to a transparent material. In this case, the width of the band gap also decreases with increasing magnetic field strength. This is an interesting effect which is similar to the metal-insulator transition that occurs in semiconductors.

II. THE EFFECT OF A MAGNETIC FIELD ON THE PHOTONIC BAND STRUCTURE

We consider a 2D metallic photonic crystal made from two rectangular metallic pillars B and C with dielectric constants ϵ_b and ϵ_c, infinite in the z direction. The metallic pillars are periodically arranged in a 2D (x-y) plane and the length of the pillars lies along the z direction. In other words, the structure is homogeneous in the z direction and periodic in the x and y directions. The unit cells are arranged in a simple tetragonal lattice. In each unit cell the opening domain has a square shape, and is empty (i.e., an air space) with a dielectric constant ϵ_a [13]. A schematic diagram of the MPC is shown in Fig. 1. The cross-sectional area of the pillars is of the order of 40 000 nm^2 and the length is of the order of several hundred micrometers. These rods are generally treated as bulk metals in the photonic crystal literature. Hence the structure considered here is a three-dimensional system having periodicity in 2D. It is well known that metals exhibit gyroelectric behavior in the presence of a magnetic field, and we have included the gyroelectric behavior in our formulation.

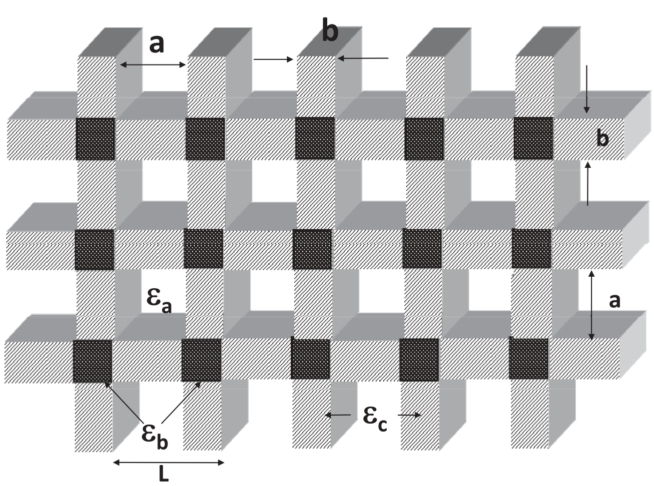

FIG. 1. Schematic of the dielectric function in a 2D separable rectangular MPC. The large white square regions have a dielectric constant ϵ_a, while the small dark square and rectangular regions have dielectric constants ϵ_b and ϵ_c, respectively. The parameters a and b give the thicknesses of the layers and $L = a + b$ is the lattice constant in both the x and y directions.

When an electromagnetic field is propagating in a metal, the conductivity of the metal is energy dependent. Using the Drude model we calculated the dielectric function of the metallic pillars in the presence of an external field. We consider that a magnetic field is applied along the z direction [i.e., $\mathbf{B} = (0,0,B)$]. In this paper we study two field configurations. In the first configuration, the $\mathbf{k}$ wave vector lies along the direction of the magnetic field. This configuration is known as the Faraday geometry. When right (+) and left (−) elliptically polarized light is propagating in the metallic crystal the dielectric function of metals is obtained as

$$\begin{aligned}\epsilon^{\pm}_{b,c}(B) &= \epsilon_L + \frac{1}{\omega}(i\sigma_{xx} \mp \sigma_{xy}),\\ \sigma_{xx} &= \frac{\omega_p^2(\gamma - i\omega)}{(\gamma - i\omega)^2 + \omega_c^2},\\ \sigma_{xy} &= \frac{\omega_p^2\omega_c}{(\gamma - i\omega)^2 + \omega_c^2},\end{aligned} \tag{1}$$

where ω_p is called the plasma energy and is obtained as $\omega_p^2 = ne^2/m\epsilon_0\epsilon_L$. In the above equations, ϵ_0 is the dielectric constant of free space and n is the electron concentration. Here e is the electronic charge, m is the mass of an electron, γ is the relaxation rate of the electrons in a pillar, and ϵ_L is the static dielectric constant of metals. The frequency ω_c is called the cyclotron frequency and is defined as $\omega_c = eB/m$. For linearly polarized light the electric function can be written as

$$\epsilon^{l}_{b,c}(B) = \epsilon_L + i\frac{1}{\omega}\sigma_{xx}. \tag{2}$$

In the second configuration we consider that $\mathbf{k}$ is perpendicular to $\mathbf{B}$ and it lies in the xy plane. This arrangement is called the Voigt geometry. Let us consider that $\mathbf{k}$ lies along the y direction, $\mathbf{k} = (0,k,0)$. Therefore in this configuration the electric field vector can lie along the z direction, $\mathbf{E} = (0,0,E)$, or the x direction, $\mathbf{E} = (E,0,0)$. When the electric field lies along $\mathbf{E} = (0,0,E)$ the dielectric constant of the metallic rods is obtained as

$$\epsilon_{b,c} = \epsilon_L + \frac{i\epsilon_L\omega_p^2}{\omega(\gamma - i\omega)}. \tag{3}$$

Note that in this case the dielectric function does not depend on the magnetic field. However, when the electric field lies along $\mathbf{E} = (E,0,0)$ the dielectric constant is found as

$$\epsilon_{b,c} = \epsilon_L + \frac{\left(i\epsilon_0\epsilon_L\omega\sigma_{xx} - \sigma_{xx}^2\right) - \sigma_{xy}^2}{\epsilon_0\omega(\epsilon_0\epsilon_L\omega + i\sigma_{xx})}. \tag{4}$$

Note that in this case the expression of the dielectric constant depends on the magnetic field.

The band structure of a 2D photonic crystal was calculated by using the transfer matrix method in Ref. [13]. It is written as

$$\begin{aligned}\cos(k_xL) &= \Lambda_x(\omega,B,\eta),\\ \cos(k_yL) &= \Lambda_y(\omega,B,\eta),\end{aligned} \tag{5}$$

where $\Lambda_x(\omega,B,\eta)$ and $\Lambda_x(\omega,B,\eta)$ are found as

$$\begin{aligned}\Lambda_x(\omega,B,\eta)\\ &= \cos\left[b\sqrt{\left(\frac{\omega}{c}\right)^2\frac{\zeta(B)}{2}-\eta^2}\right]\cos\left[a\sqrt{\left(\frac{\omega}{c}\right)^2\frac{\epsilon_a}{2}-\eta^2}\right]\\ &\quad-\left(\frac{\left(\frac{\omega}{c}\right)^2[\zeta(B)+\epsilon_a]-4\eta^2}{4\sqrt{\left(\frac{\omega}{c}\right)^2\frac{\zeta(B)}{2}-\eta^2}\sqrt{\left(\frac{\omega}{c}\right)^2\frac{\epsilon_a}{2}-\eta^2}}\right)\\ &\quad\times\sin\left[\sqrt{\left(\frac{\omega}{c}\right)^2\frac{\zeta(B)}{2}-\eta^2}\right]\sin\left[a\sqrt{\left(\frac{\omega}{c}\right)^2\frac{\epsilon_a}{2}-\eta^2}\right],\end{aligned}\tag{6}$$

$$\begin{aligned}\Lambda_y(\omega,B,\eta)\\ &= \cos\left[b\sqrt{\left(\frac{\omega}{c}\right)^2\frac{\zeta(B)}{2}+\eta^2}\right]\cos\left[a\sqrt{\left(\frac{\omega}{c}\right)^2\frac{\epsilon_a}{2}+\eta^2}\right]\\ &\quad-\left(\frac{\left(\frac{\omega}{c}\right)^2[\zeta(B)+\epsilon_a]+4\eta^2}{4\sqrt{\left(\frac{\omega}{c}\right)^2\frac{\zeta(B)}{2}+\eta^2}\sqrt{\left(\frac{\omega}{c}\right)^2\frac{\epsilon_a}{2}+\eta^2}}\right)\\ &\quad\times\sin\left[b\sqrt{\left(\frac{\omega}{c}\right)^2\frac{\zeta(B)}{2}+\eta^2}\right]\sin\left[a\sqrt{\left(\frac{\omega}{c}\right)^2\frac{\epsilon_a}{2}+\eta^2}\right].\end{aligned}\tag{7}$$

In the above equations k_x and k_y are the Bloch wave vectors along the x and y directions, respectively, and ω is the frequency of the photons. Here a and b are the lattice parameters and are related to the lattice constant as $L = a + b$. Here η is the separation constant. The relation between the dielectric constants is defined as $\zeta(B) = 2\epsilon_c(B) - \epsilon_a = \epsilon_b(B)$.

Photons with energies lying within the band gap do not propagate within a photonic crystal and photons with energies lying within bands do propagate. Therefore, the transmission coefficient $T(\omega)$ of the MPC can be calculated following the method of Ref. [14] as

$$T(\omega) = 1 - \Phi[1 - F(\omega)],\tag{8}$$

where the function $F(\omega)$ is obtained from Eq. (3) and is written as

$$F(\omega) = \frac{1}{L}\sqrt{[\arccos(\Lambda_x)]^2 + [\arccos(\Lambda_y)].^2}\tag{9}$$

Here Φ is called the Heaviside step function and has the following property: $\Phi(x) = 1$ for $x > 1$ and $\Phi(x) = 0$ for $x < 1$.

III. RESULTS AND DISCUSSION

In this section we first calculate the behavior of the dielectric function of a metal for different polarizations as a function of the normalized frequency ω/ω_p [15] for the Faraday geometry. Note that for simplicity and the ease of calculations we normalized all the frequencies by the plasma frequency (ω_p) where the relaxation rate (γ) can be ignored. In Fig. 2, the solid line shows the metal dielectric function versus the normalized frequency in the absence of the magnetic field. This figure shows that in the absence of the magnetic field all three polarizations show the same behavior. On the other hand,

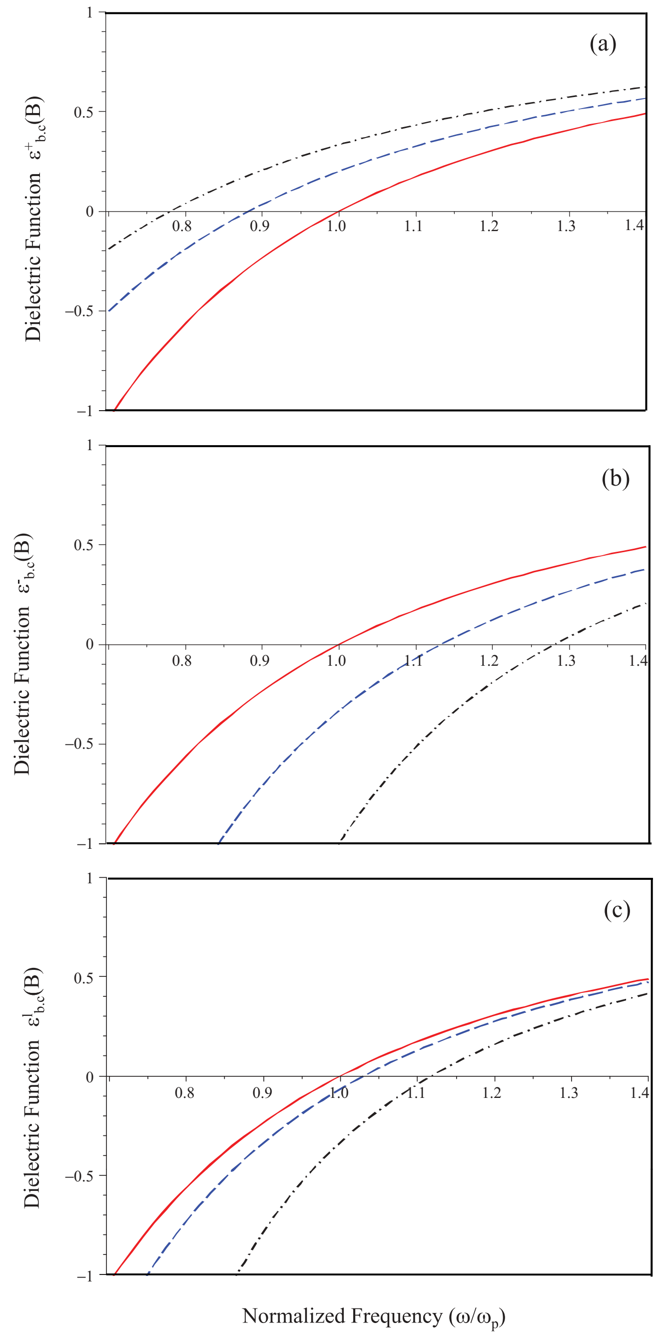

FIG. 2. (Color online) Metal dielectric function versus normalized energy. The solid, dashed, and dash-dotted curves are plotted for the normalized cyclotron frequencies $\omega_c/\omega_p = 0$, 0.25, and 0.5, respectively. (a) For right-circularly polarized light, the intercepts are $\omega/\omega_p = 1$, 0.88, and 0.78. (b) For left-circularly polarized light, the intercepts are $\omega/\omega_p = 1$, 1.13, and 1.28. (c) For linearly polarized light, the intercepts are $\omega/\omega_p = 1$, 1.03, and 1.12.

when a static magnetic field is applied all the curves shift. In the right-circular polarization the normalized frequency intercept shifts to the left, whereas in the left-circular and linear polarizations the normalized frequency intercept shifts to the right. For frequencies below the normalized frequency intercept the dielectric function is negative and the refractive index becomes an imaginary number; however, for frequencies greater than the normalized frequency intercept the dielectric function is positive and the refractive index is real. We calculate the band structure of the 2D MPC for different light polarizations and magnetic field intensities. In our calculation the crystal parameters are taken as $a = 0.3L$ and $b = 0.7L$, where L is the MPC lattice constant in the x and y directions. The background material is taken as air. The metal refractive index in our model is $n_2 = \sqrt{0.5\zeta(B)}$.

The band structure for right-circular polarization is shown in Fig. 3(a) for two values of the normalized cyclotron frequencies ($\omega_c/\omega_p = 0$ and 0.5) for the Faraday geometry. In this figure the vertical axis shows the normalized frequency $\omega_n = \omega/\omega_p$ and the horizontal axis shows the wave vector K (π/L). The pale dotted curves show the band structure in the absence of the magnetic field and the curves with crosses show the band gap in the presence of the magnetic field (i.e., $\omega_c/\omega_p = 0.5$). As one can see in the absence of a magnetic field the MPC opens a band gap between $\varepsilon_L^0 = 0.95$ and $\varepsilon_U^0 = 1.01$. The band gap has the same value for all polarizations. Here we denote by ε_L^0 and ε_U^0 the lower and upper band edges, respectively, in the absence of a magnetic field. For instance if the MPC is fabricated from aluminum with plasmon energy $\varepsilon_{pb} = 15.1$ eV and zinc with plasmon energy $\varepsilon_{pc} = 10.1$ eV, the photonic band gap lies in the ultraviolet region of the electromagnetic spectrum between $\varepsilon_L^0 = 14.3$ eV, and $\varepsilon_U^0 = 15.3$ eV. However, in the presence of a static magnetic field the width of the band gap for the normalized cyclotron frequency $\omega_c/\omega_p = 0.3$ lies between $\varepsilon_L^B = 0.90$ and $\varepsilon_U^B = 0.92$. Here we denote by ε_L^B and ε_U^B the lower and upper band edges, respectively, in the magnetic field.

Also, in the case of right-circular polarization the full band gap disappears and the normalized cutoff frequency decreases when the normalized cyclotron frequency increases. In this case the critical normalized cyclotron frequency at which the band gap completely disappears is $\omega_c/\omega_p = 0.47$, and the width of the band gap decreases on increasing the intensity of the magnetic field.

For the left-circular polarized light the band structure is plotted in Fig. 3(b). In contrast to the case of right-circular polarization, in the case of left-circular polarizations the width of the photonic band gap and the cutoff frequency increase on increase of the magnetic field. For example, the width of the band gap for the normalized cyclotron frequency $\omega_c/\omega_p = 0.3$ lies between $\varepsilon_L^B = 1.03$ and $\varepsilon_U^B = 1.13$ and the cutoff frequency shifts toward the larger frequency. Note that the frequencies of the spectra in Fig. 3 does not lie in the optical frequency range. However, the frequency of the spectra can be changed to the optical frequency range by changing the lattice constant and the size of the rods.

For the linearly polarized light the band structure is plotted in Fig. 3(c). Our calculations show that the band gap increases with magnetic field but the rate of increase in the width is lower than in the case of left-elliptically-polarized light. In this case the width of the band gap for the normalized cyclotron frequency $\omega_c/\omega_p = 0.3$ lies between $\varepsilon_L^B = 0.96$ and $\varepsilon_U^B = 1.04$.

In Fig. 4 we plot the normalized photonic band gap width for three polarizations as a function of the magnetic field (ω_c/ω_p). Our calculations show that the normalized band gap width varies linearly with the normalized cyclotron frequency for each polarization. In the case of right-circular polarization the band gap width decreases linearly on increasing the normalized cyclotron frequency (magnetic field strength). The slope of this line is -12.6. In the case of left-circular and linear polarization the band gap width increases on increasing the normalized cyclotron frequency. The slope of the decrease of the band gap width is 16 and 8.6 for left-circular and

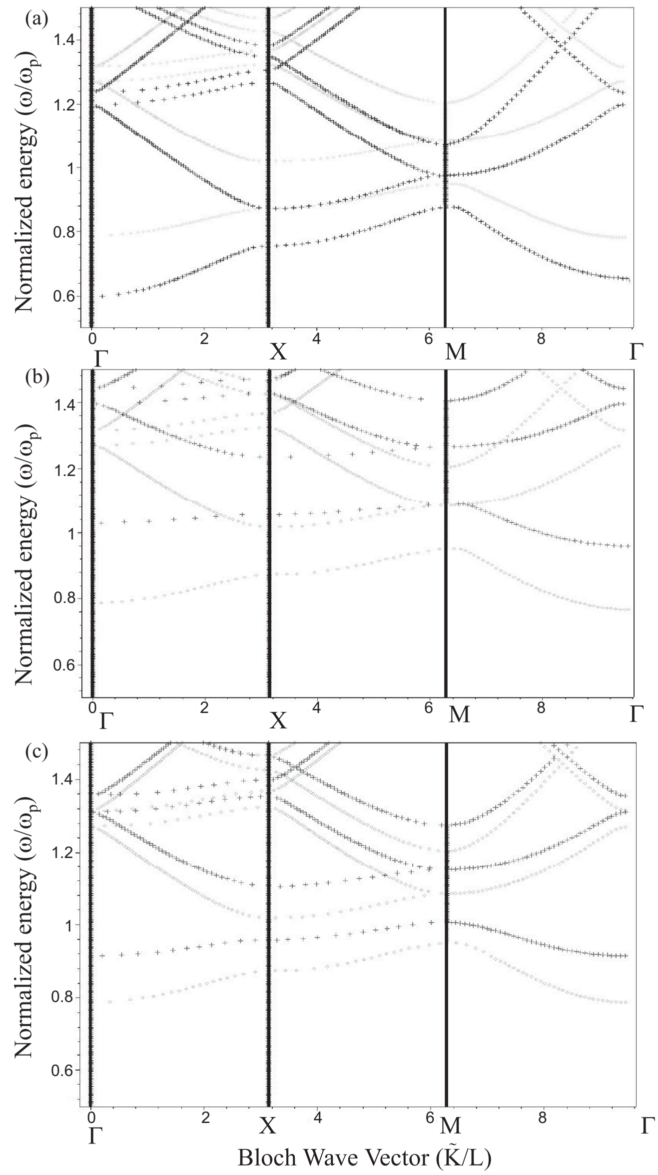

FIG. 3. Band structure of a 2D MPC with parameters $n_1 = \sqrt{0.5}$, $n_2 = \sqrt{0.5\zeta(B)}$, $a = 0.3L$, and $b = 0.7L$ for differently polarized incident light. The vertical axis is the normalized frequency $\omega_n = \omega/\omega_p$ and the horizontal axis is the normalized wave vector K/L. The curves with crosses show the band structure in the presence of the magnetic field, when $\omega_c/\omega_p = 0.3$. The second complete PBG occupies the normalized frequency regions [0.90,0.92], [1.03,1.13], and [0.96,1.04] for right-circularly (a), left-circularly (b), and linearly polarized (c) incident light, respectively. The pale dotted curves show the band structure when the normalized cyclotron frequency is $\omega_c/\omega_p = 0$. In the absence of a magnetic field the MPC opens a band gap in the [0.95,1.01] interval.

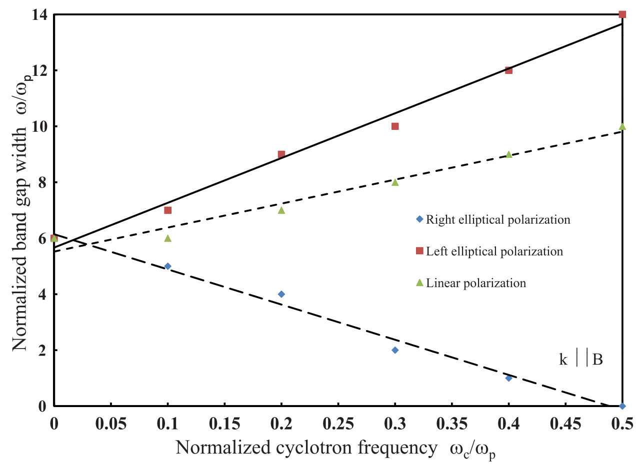

FIG. 4. (Color online) The normalized photonic band gap width versus the normalized cyclotron energy for the Faraday geometry.

linear polarization, respectively. Note that in the absence of the magnetic field the width of the band gap is the same for all polarizations.

We have also calculated the normalized photonic band gap for the Voigt geometry. The results are plotted in Fig. 5 as a function of the normalized magnetic field. Our calculations show that the photonic band gap width decreases with increasing normalized cyclotron frequency when the electric field is perpendicular to the magnetic field, whereas the band gap does not change with the cyclotron frequency when the electric field is parallel to the magnetic field. On the other hand, in the Faraday rotation for the right- and left-circular polarizations the band gap width increases and decreases, respectively, linearly with the cyclotron frequency. In the case of the linear polarization in the Faraday configuration we have also an increasing trend for the band gap width. The gyromagnetic effect [15–18] has been neglected since its effect is negligible here.

The transmission coefficient is plotted in Fig. 6(a) as a function of energy for LCP light. The dotted and dashed curves in the figure correspond to $\omega_c/\omega_p = 0$ and $\omega_c/\omega_p = 0.1$,

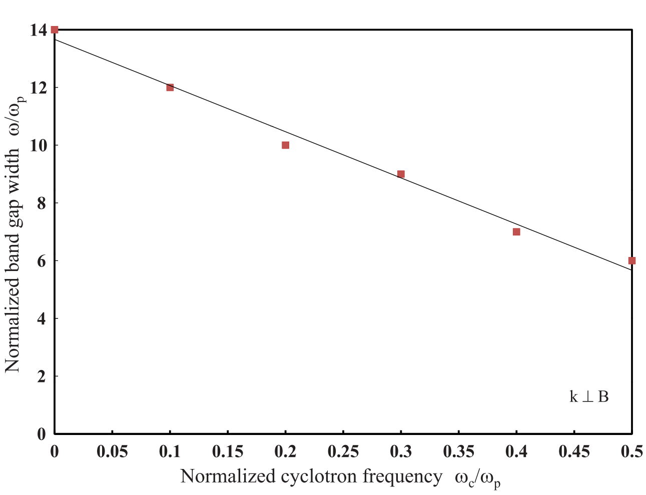

FIG. 5. (Color online) The normalized photonic band gap width versus the normalized cyclotron energy for the Voigt geometry.

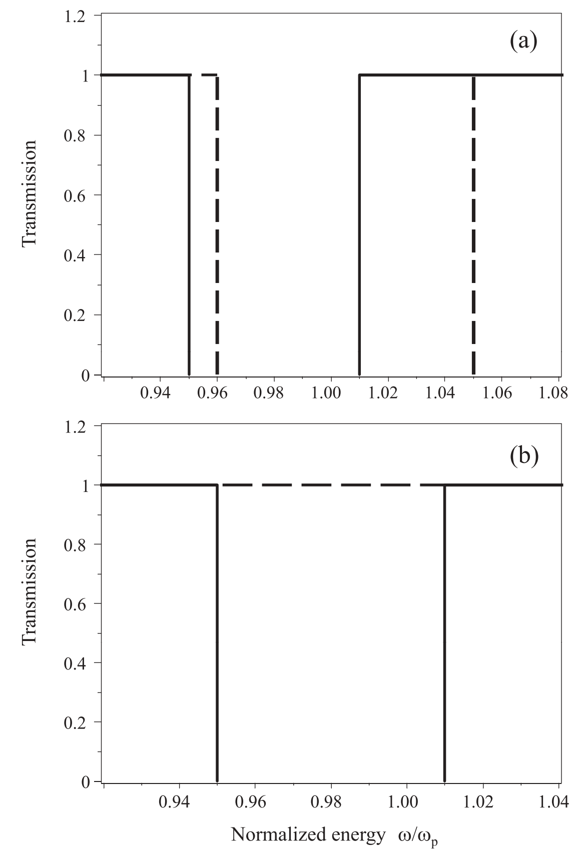

FIG. 6. The transmission coefficient as a function of energy for LCP and RCP light, respectively. The dotted and dashed curves correspond to (a) $\omega_c/\omega_p = 0$ and 0.1 and (b) $\omega_c/\omega_p = 0$ and 0.5, respectively.

respectively. Note that in the absence of magnetic field the transmission coefficient is zero between the energies $\varepsilon_L^0 = 0.95$ and $\varepsilon_U^0 = 1.01$. This means that photons with energies lying within the band gap do not propagate within a photonic crystal. Similarly, the transmission coefficient is equal to 1 outside the band gap, and photons with energies lying within bands propagate. In the presence of a magnetic field the transmission coefficient edges for the LCP light shift to new positions at $\varepsilon_L^B = 0.98$ and $\varepsilon_U^B = 1.06$ (see the dashed lines). This means that LCP light with photon energy lying between ε_L^0 and ε_L^B is totally transmitted in the presence of a magnetic field, whereas in the absence of a magnetic field the photon is totally reflected in this energy range. Similarly, LCP light with photon energy lying between ε_U^0 and ε_U^B is totally reflected in the magnetic field, whereas in the absence of a magnetic field it is totally transmitted. This means that the transmission of light can be switched on and off using the external field. This effect might be used to make photonic switches.

For RCP light the transmission coefficient is shown in Fig. 6(b) where the dotted and dashed curves are plotted for $\omega_c/\omega_p = 0$ and $\omega_c/\omega_p = 0.5$, respectively. Note that for $\omega_c/\omega_p = 0$ the transmission coefficient is zero between the energies $\varepsilon_L^0 = 0.95$ and $\varepsilon_U^0 = 1.01$. In the presence of the magnetic field the transmission coefficient edges located at ε_L^0 and ε_U^0 disappear (see the dashed line). In other words, for a certain value of the magnetic field the system switches to a transparent state for all energies of RCP light and the band gap disappears. This effect is similar to the metal-insulator transition which occurs in semiconductors and semiconductor nanostructures.

In summary, we have studied the effect of a magnetic field on the band structure of 2D MPCs. It is found that for LCP light the band gap increases with increase of the magnetic field. The band edges also shift to the right, and this implies that near the band edges the system switched from a transmitting to a reflecting state. This is an interesting effect which might be used to make photonic switches. On the other hand, for RCP light it is found that for a certain value of the magnetic field a 2D MPC transforms to a transparent material. This is similar to the metal-insulator transition that occurs in semiconductors.

ACKNOWLEDGMENTS

One of the authors (A.H.) is grateful to the Ontario Graduate Scholarship program for financial support in the form of a research scholarship.

[1] John D. Joannopoulos, Steven G. Johnson, Joshua N. Winn, and Robert D. Meade, *Photonic Crystals: Molding the Flow of Light*, 2nd ed. (Princeton University Press, Princeton, NJ, 2008).
[2] M. M. Sigalas, C. T. Chan, K. M. Ho, and C. M. Soukoulis, Phys. Rev. B **52**, 11744 (1995).
[3] Shanhui Fan, Pierre R. Villeneuve, and J. D. Joannopoulos, Phys. Rev. B **54**, 11245 (1996).
[4] A. De Lustrac, J.-M. Lourtioz, T. Brillat, A. Ammouche, E. Akmansoy, and F. Gadot, J. Appl. Phys. **85**, 8499 (1999).
[5] M. Popov, M. Qiu, C. Simovski, and S. He, Microwave Opt. Technol. Lett. **25**, 236 (2000).
[6] A. Moroz, Phys. Rev. B **66**, 1151091 (2002).
[7] L. F. Marsal, J. Ferrél-Borrull, J. Pallarès, and M. A. Ustyantsev, Opt. Commun. **274**, 293 (2007).
[8] C. S. Kee, J. E. Kim, and H. Y. Park, Phys. Rev. E **57**, 2327 (1998).
[9] C.-S. Kee, H. Lim, Y.-K. Ha, J.-E. Kim, and H. Y. Park, Phys. Rev. B **64**, 085114 (2001).
[10] A. Figotin, Y. A. Godin, and I. Vitebsky, Phys. Rev. B **57**, 2841 (1998).
[11] Z. Wang, Y. D. Chong, J. D. Joannopoulos, and M. Soljačić, Phys. Rev. Lett. **100**, 013905 (2008).
[12] J. X. Fu, R. J. Liu, and Z. Y. Li, Europhys. Lett. **89**, 64003 (2010).
[13] M. Singh and A. Hatef, Opt. Commun. **284**, 2363 (2011).
[14] Michael Scalora, Jonathan P. Dowling, Charles M. Bowden, and Mark J. Bloemer, Phys. Rev. Lett. **73**, 1368 (1994).
[15] L. Qi, Z. Yang, F. Lan, X. Gao, and Z. Shi, Phys. Plasmas **17**, 042501 (2010).
[16] O. Mayrock, S. A. Mikhailov, T. Darnhofer, and U. Rössler, Phys. Rev. B **56**, 15760 (1997).
[17] Yuriy A. Kosevich, Solid State Commun. **104**, 321 (1997).
[18] *Novel Optical Materials and Applications*, edited by Iam-Choon Khoo, Francesco Simoni, and Cesare Umeton (John Wiley and Sons, New York, 1997), p. 295.