Design of Linear Magnetic Field Sensor Based on Periodically Magnetized Cold Plasma

Nisha[1], Narendra Kumar[1], Bhuvneshwer Suthar[2*]

[1]*Department of Physics, SLAS, Mody University of Science and Technology, Lakshmangarh 332311, Sikar, Rajasthan, India*

[2]*Department of Physics, Govt Dungar College, Bikaner 334001, Rajasthan, India*

Abstract

We have analyzed the impact of a linear magnetic field on the photonic band gaps exhibited by bulk cold plasma, under external square-wave-like periodic magnetic field of fixed magnitude, conceived as an extrinsic photonic crystal. Here photonic band gaps are determined using transfer matrix method (TMM). Here, the impact of an additional linear magnetic field is determined on the band gaps of plasma photonic crystal with constant magnitude of square like periodic magnetic field, for normal incidence. We determine how the additional and magnetic magnetic field affects the photonic band structure (PBS) and reflectance for such extrinsic photonic crystal. It is noted that, as we increase the additional applied magnetic field, the central frequency of band gaps is shifted toward higher frequency regions in GHz. The band edge increases linearly with the applied magnetic field. The shifting in lower band edge less as compared to upper edge. Sensor is a device which detect the stimuli and give output, and many physical parameters can be measured by sensors. The shifting of band edges can be utilized in design of magnetic field sensor. Here shifting in band gaps by variation in the additional applied magnetic field are determined. The larger value of sensitivity gives a good result for sensing-based application. This analysis is based on the band gaps of extrinsic photonic crystal, and can be employed in design of magnetic field sensor with good sensitivity. Moreover, it can find applications in tunable optical devices.

Keywords: Extrinsic, Magnetized, Magnetic field, Sensor, Reflectance, Cold plasma, Photonic crystals.

Address of correspondence
Dr. Bhuvneshwer Suthar, Department of Physics, Govt Dungar College, Bikaner 334001, Rajasthan, India
Email: bhuvneshwer@gmail.com

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Introduction

First, the photonic crystal (PC) field was initiated in 1987 after two pioneering works done simultaneously by Yablonovitch and John [1-3]. These crystals disallow the propagation of electromagnetic wave, due to scattering of propagating wave, within a certain frequency range called photonic band gap (PBG). Photonic band gap materials are also known as photonic crystal. Photonic crystal is a periodic optical nanostructure that disturbs the motion of photons. With developments in nano-science and nanotechnology, plasma has become a very versatile material for photonic devices. Plasma is described as electrically neutral medium comprised of negatively and positively charged particles, and unlike general materials, plasma does not exist freely under normal conditions. As fourth states of matter, it was first investigated in the 1920s by chemist Irving Langmuir. It is generated by heating or placing a neutral gas to a strong electromagnetic field when the ionized gaseous substance offers increased electrical conductivity, and hence the applied fields demonstrate the behavior of the matter known as plasma [4]. Plasmas are described and categorized by many characteristic properties, including temperature, degree of ionization, and density [5].

One-dimensional (1D) plasma photonic crystal (PPC) was designed by Hojo and Mase in 2004, where the dispersion relation has been analyzed for different plasma frequencies and layer thicknesses [6]. Such PPCs are known as intrinsic plasma photonic crystals. In 1DPPCs, there are two kinds of materials as alternate layers. On the other hand, owing to presence of external periodic magnetic field, the extrinsic plasma photonic crystal is created from bulk plasma that is induced as a periodic structure [7, 8]. Hence, extrinsic plasma photonic crystals are found from bulk material, which is effected by externally applied periodic field in space.

In recent years, plasma photonic crystals have attracted considerable attention due to their tunable characteristics rather dielectric PC. Several research papers have been devoted to optical properties of single layer materials to learn the phenomena of optics behind such materials [1, 4]. King et al. [8] reported the tunable photonic band structure for extrinsic photonic crystals in which cold plasma layer placed under influence of applied an external periodically varying magnetic field. In this research, the impact of variations in electron density and the thickness of plasma layers were taken changeable. By changing the magnitude of the applied external magnetic field, we observe its impact on band gaps. If we apply a linear magnetic field in addition to periodic magnetic field and photonic band gaps are affected as determined by transfer matrix method. Extrinsic photonic crystal band gaps are controlled externally by applying a periodic magnetic field. We can change the magnitude of the magnetic field, which affect the band gaps. If we apply a linear magnetic field in addition to periodic magnetic field, the photonic band gaps are highly affected as determined by transfer matrix method.

We plot the reflection spectra for different values of linear magnetic field and find that, if we change the magnitude of the linear magnetic field, band gaps are shifted. In other words, the external magnetic field affects photonic band gaps. On the basis of the shifting in the band gaps, we can identify the strength of the magnetic field. Here magnetic field acts as stimulus which changes the band gap positions. Thus, we can say that plasma photonic crystal (PPC) can be utilized as magnetic field sensor.

Theoretical Study

We consider bulk cold plasma with periodic magnetic field, which induces 1D plasma photonic crystal periodicity, and the schematic diagram is shown in Fig1. The dispersion relation and reflection spectra for such 1-D extrinsic plasma photonic crystal (PPC) are computed by using transfer matrix method [9,10].

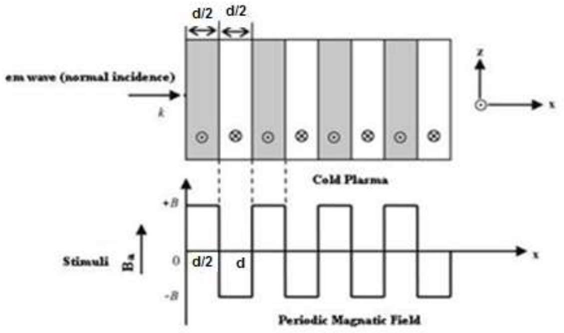


Figure 1 Schematic diagram of 1-D plasma photonic crystal by applying periodic magnetic field on bulk plasma [7].

Here,

$$\begin{pmatrix} \mathbf{a_{m-1}} \\ \mathbf{b_{m-1}} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{pmatrix} \begin{pmatrix} \mathbf{a_m} \\ \mathbf{b_m} \end{pmatrix} \tag{1}$$

where the matrix elements are expressed as

$$A = e^{ik_1 a}\left[\cos k_2 b + \frac{1}{2} i\left(\frac{k_2}{k_1} + \frac{k_1}{k_2}\right)\sin k_2 b\right]$$

$$B = e^{-ik_1 a}\left[\frac{1}{2} i\left(\frac{k_2}{k_1} - \frac{k_1}{k_2}\right)\sin k_2 b\right]$$

$$c = e^{ik_1 a}\left[-\frac{1}{2} i\left(\frac{k_2}{k_1} - \frac{k_1}{k_2}\right)\sin k_2 b\right]$$

$$D = e^{-ik_1 a}\left[\cos k_2 b - \frac{1}{2} i\left(\frac{k_2}{k_1} + \frac{k_1}{k_2}\right)\sin k_2 b\right]$$

Wave propagation in periodic media is very similar to the electronic motions in solid crystal lattice that is governed by the Kronig–Penney model [4] that is numerically identical to propagation of electromagnetic waves in periodic layered media. Some of the functions used in the model, that is, Bloch wave is used in a periodically-repeating environment, that is, electronic motion through crystal. A periodic layered medium is conceived as similar to a one-dimensional lattice for photonic motion through them.

$$\mathbf{n^2(x + d) = n^2(x)} \tag{2}$$

where d is the period.

In term of our column vectors representation, the periodic condition for Bloch wave is simply

$$\begin{pmatrix} a_m \\ b_m \end{pmatrix} = e^{-iKd} \begin{pmatrix} a_{m-1} \\ b_{m-1} \end{pmatrix} \tag{3}$$

It follows that the column vector of the Bloch wave satisfies the following Eigen problem

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} a_m \\ b_m \end{pmatrix} = e^{iKd} \begin{pmatrix} a_m \\ b_m \end{pmatrix} \tag{4}$$

The phase factor e^{iKd} is thus the Eigen value of translation matrix (A, B, C, D) and is given by

$$e^{iKd} = \frac{1}{2}(A + D) \pm \left\{\left[\frac{1}{2}(A + D)\right]^2 - 1\right\}^{\frac{1}{2}} \tag{5}$$

The Eigen vectors corresponding to Eigen values of equation (6) are obtained from equation (5) and are

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = \begin{pmatrix} B \\ e^{iKd} - A \end{pmatrix} \tag{6}$$

The Bloch wave that result is considered as the Eigen vector of the translational matrix with Eigen values $e^{\pm iKd}$ given by (6). The two eigen values in equation (6) are the inverse of each other since the translation matrix is unimodular [7].

The dispersion relation between ω, β and K for the Bloch wave function is

$$\mathbf{K}(\beta, \omega) = \frac{1}{d}\cos^{-1}\left[\frac{1}{2}(A + D)\right] \tag{7}$$

The band structure for a periodic layered medium as obtained from equation (7) for TE and TM waves. The dispersion relation between ω and K in this case can be written as

$$\cos Kd = \cos k_1 a \cos k_2 b - \frac{1}{2}\left(\frac{n_2}{n_1} + \frac{n_1}{n_2}\right)\sin k_1 a \sin k_2 b \tag{8}$$

Or

$$\mathbf{K = \frac{1}{d}\cos^{-1}\left(\cos k_1 a \cos k_2 b - \frac{1}{2}\left(\frac{n_2}{n_1} + \frac{n_1}{n_2}\right)\sin k_1 a \sin k_2 b\right)}$$
(9)

where $k_1 = \left(\frac{\omega}{c}\right)n_1$ and $k_2 = \left(\frac{\omega}{c}\right)n_2$

When a normal monochromatic plan wave is incident on to a periodic layered medium, a Bloch wave is generated in the medium. If the Bloch wave falls in the so-called forbidden bands, such wave cannot propagate in the medium. Thus, the light energy is expected to be totally reflected, and the medium act as a high reflectance reflector for the incident wave. We now consider the reflection of electromagnetic wave through a periodic layered medium. Periodic layered medium consists of N unit cell (i.e., N pairs of layers).

The coefficient of reflection given by

$$\boldsymbol{r_N = \left(\frac{b_0}{a_0}\right)_{b_N=0}} \quad \textbf{(10)}$$

The Nth power of unimodular matrix can be simplified by the following matrix:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}^N = \begin{pmatrix} AU_{N-1} - U_{N-2} & BU_{N-1} \\ CU_{N-1} & DU_{N-1} - U_{N-2} \end{pmatrix} \quad \textbf{(11)}$$

where

$$U_N = \frac{\sin(N+1)Kd}{\sin Kd}$$

The coefficient of reflection is obtained by

$$r_N = \frac{CU_{N-1}}{AU_{N-1} - U_{N-2}} \quad \textbf{(12)}$$

The reflectance is obtained by taking the absolute square of r_N

$$|\gamma_N|^2 = \frac{|C|^2}{|C|^2 + \left(\frac{Sin\,Kd}{Sin\,NKd}\right)^2} \quad \textbf{(13)}$$

For magmetized cold plasma [7] $\varepsilon(\omega) = \varepsilon_{real} + i\varepsilon_{im}$, where ε is the dielectric constant and ω is the angular wave frequency

$$\boldsymbol{\varepsilon_{plasma}(\omega) = 1 - \frac{\omega_{pe}^2}{\omega^2\left[\left(1 - i\frac{\gamma}{\omega} \mp \frac{\omega_{le}}{\omega}\right)\right]}} \quad \textbf{(14)}$$

where

$$\boldsymbol{\omega_{pe} = \left(\frac{ne^2}{\varepsilon_0 m_e}\right)^{\frac{1}{2}}}$$

is the electron plasma frequency with m_e and n are the electronic mass and density and parameter γ is the effective collision frequency.

Here, ω_{le} is gyro frequency under the applied periodic magnetic field (B_a), where $\boldsymbol{\omega_{le} = \left(\frac{eB}{m_e}\right)}$

For right-handed polarization (RHP): $\boldsymbol{\varepsilon(\omega) = \varepsilon_1}$ for plasma, where - sign is used in eq. (14). In case of left-handed polarization (LHP): $\boldsymbol{\varepsilon(\omega) = \varepsilon_2}$, where + sign is used. The dispersion relation for the (PPC) is given by [9,10].

$$\boldsymbol{\cos Kd = \cos(k_1 a)\cos(k_2 b) - \frac{1}{2}\left(\frac{\sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2}} + \frac{\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1}}\right)\sin k_1 a \sin k_2 b} \quad (15)$$

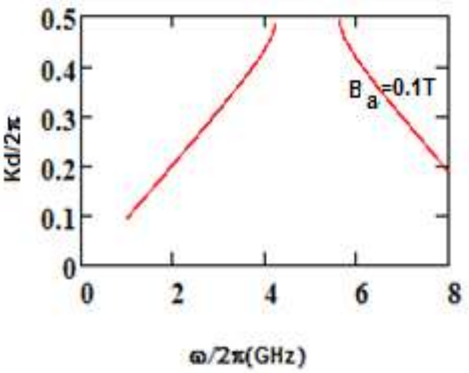
where consider $\boldsymbol{n_1 = \sqrt{\varepsilon_1}}$ and $\boldsymbol{n_2 = \sqrt{\varepsilon_2}}$.

Results and Discussion

In section, the effect of an additional magnetic field of different strength, in addition to the periodic the result magnetic field generating PPC, is studied. Here, the parameters of the cold plasma in extrinsic photonic crystal are chosen as a=b= 15mm for a square-wave- like periodic magnetic field with magnitude B = 1T, number density of electron n = 8, number of unit cells N = 30, and collision frequency.

The dispersion relation for a structure have been derived with Bloch equation by using the transverse matrix method, derived by the equation (10) and the reflection can be obtained by equation (14). Now we plot the graph for dispersion relation and reflectance (dispersion K vs frequency in GHz) and (reflectance vs frequency in GHz) by changing the externally applied magnetic field Ba. We take the value of periodic magnetic B = 1T for all values of additional magnetic field. Additional magnetic field is taken as Ba = 0.1T, 0.2T, 0.3T, 0.4T, 0.5T, and 0.6T.

Here the Photonic band structures (PBS), and reflectance for each value of external magnetic field are plotted and shown in Figs. 2-7. We compare these curves and find important insights that make the basis for sensing the additional magnetic field with a good sensitivity. It is clear from above all figures that the band gap is shifted towards the higher frequency values with increase in the additional magnetic field applied parallel to z-axis. The upper edge of photonic bandgap is shifted larger as compared to lower edge of bandgap.



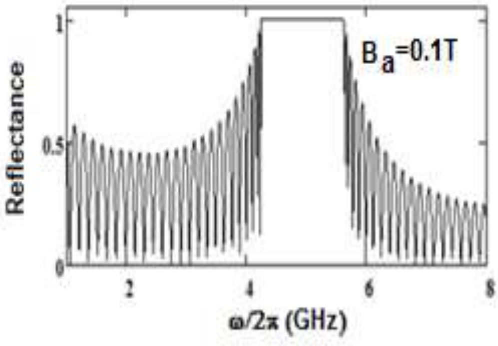


Figure 2: Dispersion and Reflectance vs frequency $\omega/2\pi(GHz)$ plots at additional magnetic field $B_a = 0.1T$

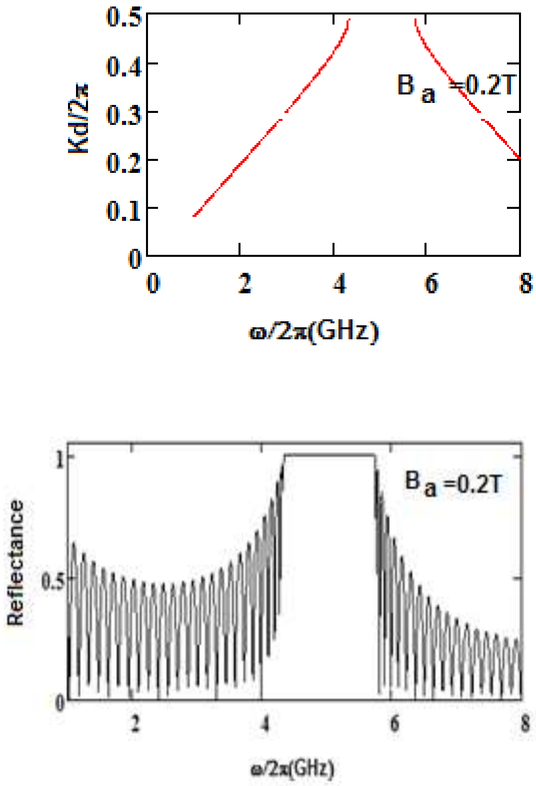
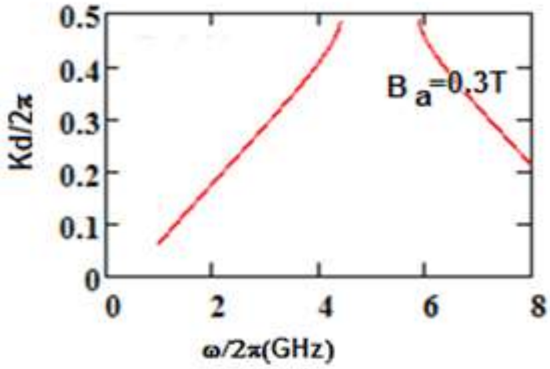


Figure 3: Dispersion and Reflectance vs frequency $\omega/2\pi(GHz)$Plots at additional magnetic field $B_a = 0.2T$



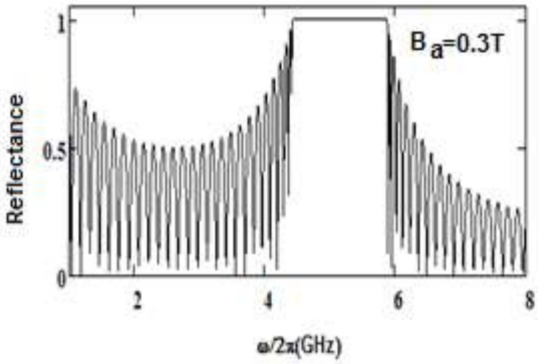


Figure 4: Dispersion and Reflectance vs frequency $\omega/2\pi(GHz)$ plots at additional magnetic field $B_a = 0.3T$

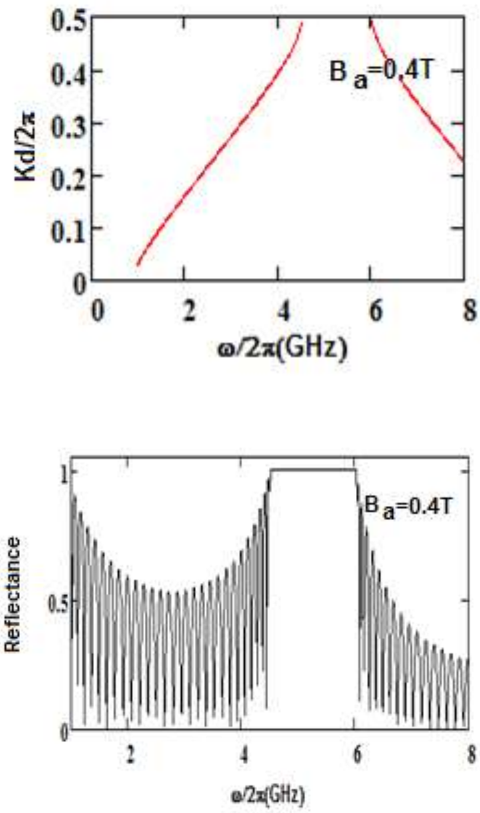
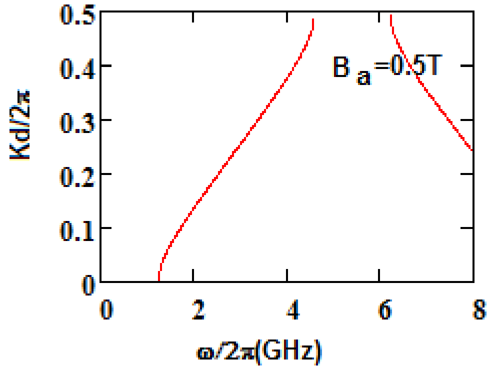


Figure 5: Dispersion and Reflectance vs frequency $\omega/2\pi(GHz)$ plots at additional magnetic field $B_a = 0.4T$



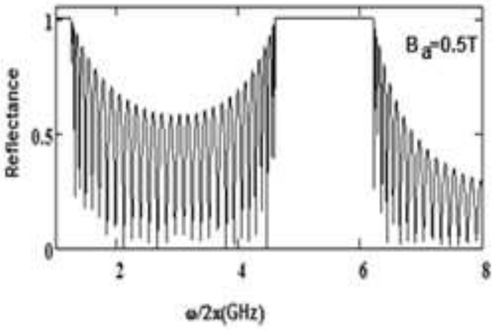


Figure 6: Dispersion and Reflectance vs frequency $\omega/2\pi(GHz)$ plots at additional magnetic field $B_a = 0.5T$

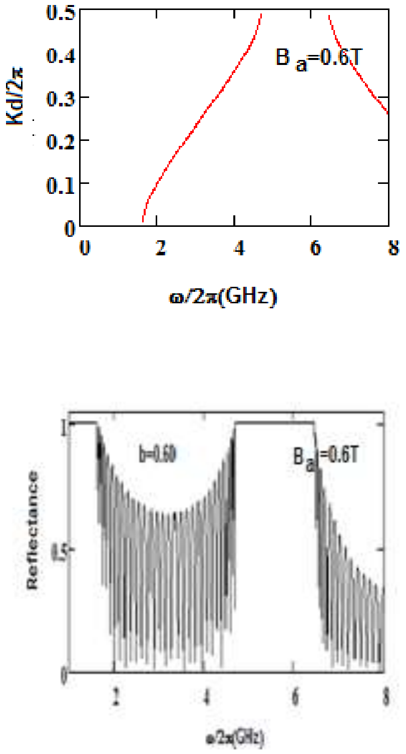


Figure 7: Dispersion and Reflectance vs frequency ω/2π (GHz) Plots at additional magnetic field $B_a = 0.6T$

First these curves shows that reflection and PBS curves are in a good agreement as the media is considered as low less with low collision frequency [8]. As we increase the additional field the lower and upper band edges are shifted to higher frequency side and the central frequency is shifted towards higher values in each case. Looking into these curves we find that there is a linear increase in the lower band edge, where as there is monotonic exponential type increase in the upper band is as shown in Fig. 8. Comparing these curves, we find that the band is not considerably affected with the variation in the additional magnetic field (Refer Fig. 8), while the central frequency increase linearly with an increase in the additional magnetic field. Thus, here we find that additional magnetic field plays an important role in shifting of band and these changes can be considered as a basis in design of linear magnetic field sensors. Table 1 shows the results obtained in various cases.

Table 1: Effect of additional constant linear magnetic field on the band gap obtained in extrinsic plasma photonic crystal (PPC)

s.no.	Additional field B_a (Tesla)	Lower Edge (GHz)	Upper Edge (GHz)	Band Gap (GHz)	Centre Frequency (GHz)
1	0.05	4.2	5.56	1.36	4.88
2	0.1	4.25	5.62	1.37	4.935
3	0.15	4.3	5.68	1.38	4.99
4	0.2	4.35	5.74	1.39	5.045
5	0.25	4.39	5.8	1.41	5.095
6	0.3	4.43	5.87	1.41	5.15
7	0.35	4.48	5.94	1.46	5.21
8	0.4	4.52	6.02	1.5	5.27
9	0.45	4.56	6.11	1.55	5.335
10	0.5	4.6	6.21	1.61	5.405
11	0.55	4.64	6.32	1.68	5.48
12	0.6	4.69	6.45	1.76	5.57

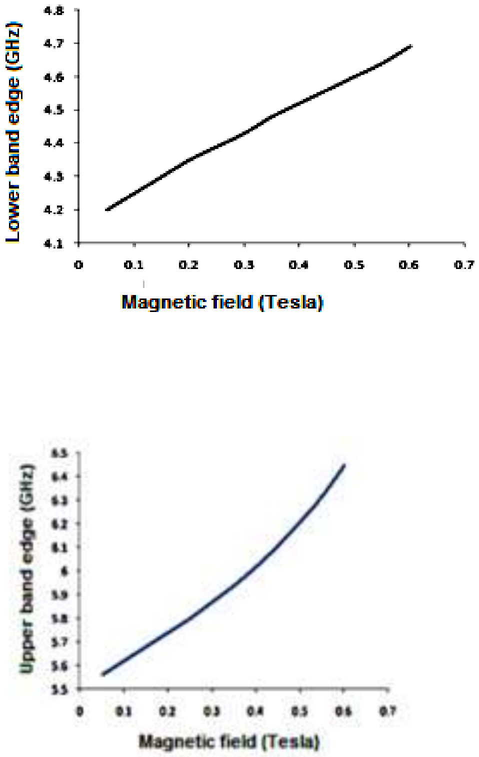
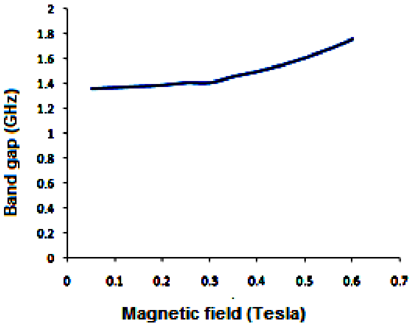


Figure 8: Variations of lower band edge and upper band edges with additional linear magnetic field B_a



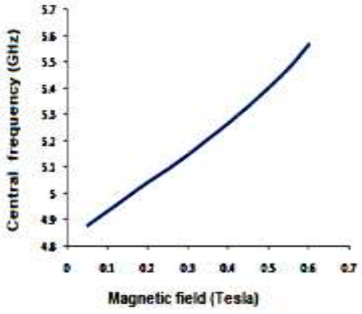


Figure 9: Variations of band gap and central frequency with additional linear magnetic field B_a

From Fig. 9, the values of band edge, band gap and central frequency are listed in Table 1 by which we can also understand the effect of magnetic field.

Plasma photonic crystal can be used in frequency-selective, loss-less reflection filters, switches, optical amplifiers, and in motive electronics, such as, collision avoidance radar. Based on the cyclotron resonance, it may be utilized in heating for fusion plasma diagnostic tools in the frequency range 60-200GHz, and also having medical and biological applications including microwave resonance based on imaging tool in the frequency range 40-80GHz.

Such PCs may also be referred in wide bandwidth communication, Mm waveguides, fast electronics communication, laser, remote sensing, and similar optical devices for improved performance. Magnetic field sensors are used in many industrial applications, such as in contact less current sensing, linear and angular position, rotation sensing, position tracking and local navigation using artificial field, detection of conducting objects using eddy current, detection of ferromagnetic object, and magnetic field exhibits far higher sensitivity.

Conclusion

In this work, we analyze the effect of additional linear magnetic field on the photonic band gaps exhibited by bulk cold plasma, under external square-wave-like periodic magnetic field, considered as an extrinsic photonic crystal. Here, the impact of an additional linear magnetic field on PBGs of plasma photonic crystal, with constant magnitude of square like periodic magnetic field, are determined for normal incidence. Further, we emphasize on how the additional and magnetic magnetic field tailors the photonic band structure (PBS) and reflection for such a 1D PPC.

It is observed that, if we increase the additional applied magnetic field, then the centre of band gaps are shifted toward higher frequency regions in GHz. The band edge increases linearly with the applied additional linear constant magnetic field. Lower edge is shifted less compared to upper edge. The shifting of band edges can have very interesting application in design of magnetic field sensor. Sensor is a device which detect the stimuli and give output, many physical parameters can be measured by sensors. Here changes in band gaps or shifting by variation in the additional applied magnetic field are detected. The sensitivity parameter is defined as ratio of change in frequency per unit magnetic field. The larger value of sensitivity shows a good result for sensors-based application. Thus we can say this theoretical analysis of extrinsic PPC, based on the band gap, can be employed in design of magnetic field sensor with good sensitivity [11]. It can be also used in tunable optical filters and other devices.

References

1. Joannopoulos, J.D. Johnson, S.G., Winn, J.N., Meade, R.D. Photonic Crystals: Molding the Flow of Light, Second Edition, Princeton University Press, Princeton, 2008.
2. E. Yablonovitch, Phys. Rev. Lett. 58, 2059, 1987.
3. S. John, Phys. Rev. Lett. 58, 2486, 1987.
4. Kumar N. and Rostami A. Novel Features and Perspectives of Photonic Crystals, Lambert Academic Publishing GmbH & Co. KG, Saarbrücken, Germany, 2012.
5. N. Kumar and S. P. Ojha, Progress In Electromagnetics Research 80, 431, 2008.Development of and Basic Property Research Trends in Environment-friendly Piezoelectric Materials, Tae Kwon Song, Seung Eon Moon, Physics and High Technology, 2013, 22(1/2):2.
6. H. Hojo and A. Mase, Journal of Plasma and Fusion Research 80, 89, 2004.
7. L. Qi and X. Zhang, Solid State Communications 151, 1838, 2011.
8. King, T.C., et al. Physica E, 67, 7, 2015.
9. R. Kumar. A. S. Kushwaha and S. K. Srivastava, Optik 126 1324.2015.
10. P. Yeh, Optical Waves in Layered Media, John Wiley & Sons, Singapore, 1991.
11. N. Kumar, S. Kaliramna, and M. Singh, Design of Cold Plasma Based Ternary Photonic Crystal for Microwave Applications, Silicon Springer Nature, Oct 2021. https://doi.org/10.1007/s12633-021-01405-9.