Magnetic field induced multichannel tunable filter properties of photonic band gap materials

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Abstract: we have explored the tunable multichannel characteristics of one-dimensional (1D) plasma photonic structure in presence of static magnetic field applied externally parallel and anti-parallel to the direction of propagation under normal incidence. We have theoretically examined the transmission characteristics of the binary photonic design consisting of alternate layers of CaF2 and magnetic cold plasma layers by means of transfer matrix method (TMM) which is amongst the one of the popular techniques for simulating 1D multilayer periodic structures based on MATLAB. The proposed structure possess $N-1$ number of distinct transmission peaks, each of unit transmission called as transmission channels in transmission spectra for given the number of periods $N>1$. In this study $N$ varies from 2 to 6 in steps of 1 to get 1 to 5 transmission channels respectively. Further we have also investigated how these transmission channels can be repositioned inside PBG by applying the static magnetic field (B) externally under right hand polarization (RHP) and left hand polarization (LHP) configurations for given $N$ at $B = 0T, 0.02T, 0.04T$ and $0.06T$. The reason behind the existence of these transmission channels is due to the superposition of evanescent and propagating waves inside plasma and dielectric layers respectively. The existence of these transmission channels inside PBG is different from the transmission bands which are formed due to the interference of forward and backward propagating waves. Besides this the tuning sense of the transmission channels at fixed B applied parallel or anti parallel to direction of periodicity, by changing the angle of incidence corresponding to TE and TM polarization case has also been examined to get some more useful and interesting tunable multichannel characteristics of the current design which cannot be obtained in conventional PPCs.

1. Introduction

The discovery of pioneering work of photonic band gap (PBG) and photon localization by two scientists Yablonovitch and John in 1987 [1, 2] attracted the attention of various research groups worldwide. PCs have amazing optical properties to control the propagation light due to the existence of PBGs which result from multiple Bragg scattering of light from the interface separating two media of the multilayer periodic structure [3-10]. PBGs are optical counterparts of the electronic band gaps (EBGs) in semiconductors [11-14]. PCs are periodic structures in which materials layers of different refractive indices like dielectric, polymers, metals and superconductor modulate periodically [15-22]. These engineered structures have variety of applications such as omnidirectional reflector, high Q-microcavities, all-optical switches, optical transistors, waveguides, filters, biosensors and others [23-32]. Beside this PCs can also be used for light trapping applications by creating deformation in the periodicity of the photonic structures [33-37]. This deformation generates a resonant tunneling mode, also called defect mode inside the photonic band gap (PBG) of structure and capable to exhibit a material-specific response profile of defect mode to external...
stimuli [38, 39]. The formation of the defect mode capable of sensing very minute change in the defect layer refractive index which are received considerable attention for designing of high performance photonic biosensors due to availability of easier and advanced photonic fabrication techniques to realize such structures [40-46]. Such 1D defective PC structures are responsive structures and are exploring new research field based on photonic sensing and technology due to their low cost and the easier fabrication techniques as compared to 2D and 3D defective PCs [47-49].

On the other hand PCs based on plasma as proposed by Hojo et al. first time in 2004 possess PBG which can be guided by altering the parameters associated with plasma like density and thickness of constituent material layers in microwave region [50]. They name this structure as plasma photonic crystals (PPCs), whose PBG characteristics can be tuned contrary to the PBGs characteristics of the conventional PCs. Later on PPC has been modified by replacing non-magnetic plasma layer with magnetic cold plasma layer to modify the structure. These modified structures with tunable PBG characteristics in presence of an externally applied magnetic field are termed as magnetically tunable plasma photonic structures (MPPCs) [51-53]. Such structures have attracted more interest of the researchers worldwide due to their externally tunable magnetic field dependent EM properties and the ability to control density of electron in plasma [54]. Moreover a tremendous property of arising one or more resonant peaks each of unit transmission dependent on period number, without breaking the periodicity of the structure has been found in MPPC due to the interaction between forward and backward decaying waves inside magnetic cold plasma layer, called as evanescent waves and propagating waves in dielectric layers [39, 55]. Awasthi et al. used such properties to investigate the magnetic field induced tunable multi-channel filter properties of 1D photonic structure whose period is composed of magnetized cold plasma layer which is sandwiched between two identical layers of quartz glass in the presence of evanescent wave [56] whereas the optical properties of 1D MPPC associated with dispersion relation and PBGs corresponding to TM polarization with arbitrary magnetic declination have been theoretically investigated by Zhang et al. [57] Though in MPPCs without defect a tunable resonant mode of unit transmission can be found inside PBG, Kong et al explored the idea of doping of semiconductors to dope conventional 1D PC by magnetic cold plasma layer and suggested how a defect mode corresponding to the TE polarized wave inside PBG of 1D PPC doped with magnetic cold plasma [58] can be guided. Some other interesting optical properties of PC based on magneto-optical effects are observed by Bin et al. [59]. Besides this Qi et al. studied how the application of periodically varying external magnetic field on a single plasma layer can also be used to get some fascinating PBG properties of great importance [60]. Recently, Awasthi et al. studied magnetic field induced tunable transmission and reflection characteristics of 1D hetrostructures composed of MPPCs in microwave frequency region capable of filtering 3N-3 transmission channels for period number greater than one [61]. Aforementioned research work based on MPPC whose PBG characteristics can be externally controlled have attracted great attention in past few years due to their technological utilization in the field of photonic microwave engineering.

All the above mentioned excellent piece of research works carried by various research groups’ worldwide show the importance of externally tunable PBG properties of various 1D MPPC structures composed binary or ternary layers of magnetic cold plasma and dielectric materials. The purpose of this article is to extend the findings of Chang et al. [62] and Li et al. [63] by exploring the possibility of 1D binary MPPC structure to be used as tunable multichannel filter in microwave frequency region (3 – 7) GHz in presence of an external magnetic field in two different configurations. As far as our knowledge in this field no one has explored the multiple channels filtering capabilities of 1D binary MPPC structure between microwave frequency range 3 GHz to 7 GHz. In this paper, we have investigated the tunable transmission properties of microwave passing through the 1D MPPC whose period is composed alternating layers of two different materials with the help of standard transfer matrix method (TMM) theoretically [64-69].
2. Theoretical model and formulation

In this section we discuss the schematic of the proposed 1D plasma photonic crystal (PPC) \[\text{[air/(AB)}^N/\text{air]}\] consisting of alternating layers A and B of material CaF\(_2\) and magnetized cold plasma respectively. The entire structure has been placed inside external magnetic field \(B\) as shown in Fig. 1.

The transfer matrix formulation \([70]\) (TMM) has been adopted for simulations of the results. The period number of the structure is \(N\). Our structure is immersed in air. The thickness and refractive index of layers A and B are represented by \(d_1\) \& \(d_2\) and \(n_1\) \& \(n_2\) respectively. The refractive index of plasma layer B is further defined as \(n_2 = \sqrt{\varepsilon_2}\), here \(\varepsilon_2\) is the relative permittivity of plasma layer. The magnetic permeability of both the media is assumed to be 1 because of non-magnetic nature of their magnetic permeability. Suppose a plane wave is allowed to fall on 1D photonic structure at incident angle \(\theta_o\) with respect direction of periodicity (which is z-axis in our case) from air of refractive index 1. The electric field (E) and magnetic field (H) vectors of s- [transverse electric (TE)] and p- [transverse magnetic (TM)] polarized incident microwave are perpendicular to xz plane respectively.

In order to connect electric and magnetic field vectors of incident microwave at every interface of the structure we use TMM as \([71]\)

\[
M_i = \begin{pmatrix}
\cos \gamma_i & -\frac{i}{q_i} \sin \gamma_i \\
-iq_i \sin \gamma_i & \cos \gamma_i
\end{pmatrix},
\]

where \(\gamma_i = \frac{\alpha}{c} \sqrt{\mu_i \varepsilon_i d_i \cos \theta_i}\), the speed of light in air is \(c\), angular frequency of the incident microwave is \(\alpha\), thickness of the \(i^{th}\) layer is \(d_i\), the ray angle inside \(i^{th}\) layer is \(\theta_i\). The relative permittivity...
and permeability of \( i^{th} \) layer is represented by \( \varepsilon_i \) and \( \mu_i \) respectively. The value of \( \cos \theta_i \) in terms of incident angle \( \theta_i \) is obtained with the help of Snell’s law as
\[
\cos \theta_i = \sqrt{1 - \left( \frac{n_o \sin \theta_o}{\varepsilon_i \mu_i} \right)^2}
\]
Here \( n_o \) is the refractive index of ambient medium which is air in our case. For \( s \)- and \( p \)-polarized waves the value of \( q_i \) will be \( \frac{\sqrt{\varepsilon_i}}{\sqrt{\mu_i}} \cos \theta_i \) and \( \frac{\sqrt{\mu_i}}{\sqrt{\varepsilon_i}} \cos \theta_i \) respectively.

In the proposed 1D PPC design as shown in Fig. 1, TMM has been used as an effective tool to analyze its optical properties. For connecting electric and magnetic fields of first and last layers of whole structure as depicted in Fig. 1 TMM has been utilized as
\[
\begin{pmatrix}
E_1 \\
H_1
\end{pmatrix} = (M_A M_B) \ldots (M_A M_B) 
\begin{pmatrix}
E_{n+1} \\
H_{n+1}
\end{pmatrix}
= M^n 
\begin{pmatrix}
E_{n+1} \\
H_{n+1}
\end{pmatrix} = \begin{pmatrix}
m_{11} & m_{12} \\
m_{21} & m_{22}
\end{pmatrix} \begin{pmatrix}
E_{n+1} \\
H_{n+1}
\end{pmatrix}
\tag{2}
\]

Where \( m_{11}, m_{12}, m_{21} \) and \( m_{22} \) are representing the elements of total transfer matrix of whole 1D PPC structure in presence of an external magnetic field \( B \). The transmission coefficient of the proposed structure is defined as
\[
t = \frac{2q_o}{m_{11}q_o + m_{12}q_oq_{n+1} + m_{21} + m_{22}q_{n+1}}
\tag{3}
\]
Here \( q_o \) and \( q_{n+1} \) are corresponding to the incident (\( z < L \)) and exit (\( z > L \)) media of the structure respectively. The total length of the proposed design is \( L \). For \( s \)-polarized wave \( q_o = q_{n+1} = \sqrt{\varepsilon_o / \mu_o} \cos(\theta_o) \) whereas for \( p \)-polarized wave \( q_o = q_{n+1} = \sqrt{\mu_o / \varepsilon_o} \cos(\theta_o) \).

The transmittance of the structure can be obtained with the help of following relation as
\[
T = \frac{q_{n+1}}{q_o} |m|^2 \tag{4}
\]

Next the efforts are given to discuss how static magnetic field influences the behavior of permittivity function of cold plasma layer. The \( \omega \) and \( B \) dependent permittivity function of cold plasma layer is defined by Eq. (5) as [39, 50, 59, 72]
\[
\varepsilon_p(\omega, B) = 1 - \frac{\omega^2}{\omega_p^2 \left[ 1 - \frac{i\gamma}{\omega} \pm \frac{\omega}{\omega_c} \right]}
\tag{5}
\]
where symbols \( \omega_p \), \( \omega_c \) and \( \gamma \) are used to represent plasma frequency, gyro-frequency and collision frequency respectively of cold plasma. The negative and positive signs prior to \( \omega_c \) be used to represent the application of externally applied static magnetic field along the direction of periodicity and opposite to direction of periodicity respectively. The application of external magnetic field along the direction of periodicity is known as right-hand polarization (RHP) whereas opposite to the direction of periodicity is known as left-hand polarization (LHP) configurations. The expressions of plasma and gyro frequencies of cold plasma are given in Eqs. (6) and (7) respectively as
\[
\omega_{pe} = \sqrt{\frac{n_e^2 e}{m \varepsilon_o}}
\tag{6}
\]
\[
\omega_{ge} = \frac{eB}{m}
\]
where \(m\) is used to represent electronic mass, \(e\) is the electronic charge, \(n_e\) is the electron density and \(\varepsilon_0\) is electric permittivity of free space. The application of \(B\) along positive and negative \(z\)-axis represents RHP and LHP configurations respectively.

3. Results and discussions

In the proposed research work we have chosen structural parameters as \(n_e = 1.42\) (CaF\(_2\)) \([68]\), \(d_1 = 15\) mm, \(d_2 = 20\) mm, \(n_e = 8 \times 10^{17} \text{m}^{-3}\), \(\gamma = 4\pi \times 10^7 \text{Hz}\). For studying \(B\) dependent tunable multi-channel filter characteristics of the proposed photonic structure \((AB)^N\) we have varied the total periods number of periods \((N)\) of the structure \((AB)^N\) from 2 to 6 along with incident angle.

First we examined incident microwave frequency dependent properties of electric permittivity of cold plasma layer in the presence of external \(B\) in RHP and LHP configurations both as defined in Eq. (5). For this purpose we study the \(\omega\) and \(B\) dependent behavior of real part of electric permittivity of plasma layer we have chosen microwave frequency region which varies from 3 GHz to 7 GHz. The reason behind the selection of frequency range 3 GHz to 7 GHz is due to fact that in this frequency range cold plasma material layer becomes as an epsilon negative material which is one of single negative material (SNG).

Figs. 2(a) and 2(b) illustrate how the real part of electric permittivity \([\text{Re}(\varepsilon_B)]\) of cold plasma material layer changes with frequency of incident radiation under the influence of \(B\) applied externally along \(z\) axis (RHP) and opposite to \(z\) axis (LHP) arrangements respectively. The red, green, blue and black dashed lines curves are at different magnetic field values as mentioned in Fig. 2. It has been found in

![Fig. 2](image-url)

Fig. 2: Calculated \(\omega\) dependent \(\text{Re}(\varepsilon_B)\) of cold plasma material layer under the influence of an external \(B = 0T, 0.02T, 0.04T\) and 0.06T shown by dashed line curve of colors red, green blue and black respectively under (a) RHP and (b) LHP arrangements.

Fig. 2 show that the increase in incident microwave frequency results the corresponding increase in the value of \(\text{Re}(\varepsilon_B)\) which reaches to its maximum value in the region of investigation. Moreover application of \(B\) from 0 to 0.06 T in steps of 0.02 under RHP arrangement results further decrease in the real part of permittivity of cold plasma layer dependent on incident microwave frequency. On the other hand electric permittivity of plasma material layer increases under the influence of \(B\) which varies from 0
to 0.06T in steps of 0.02 under LHP arrangement. In both the cases Re($\varepsilon_B$) plasma layer dependent upon $\omega$ always maintain its SNG characteristics. Thus due to the different behavior of electric permittivity of plasma layer under the application of B in RHP and LHP arrangements both opens new gateway for designing of tunable SNG materials as well as associated photonic devices in microwave region. Furthermore the magnetic field B and frequency $\omega$ dependent behavior of $\varepsilon_B$ of plasma layer is of opposite nature under RHP and LHP arrangements as shown in Fig 2. This useful property may be utilized for tuning the right and left band edges of photonic band gap and increase an additional degree of freedom for controlling of photonic band gap. Beside this negative values of $\varepsilon_B$ of plasma material layer also indicate its metal like behavior which does not allow propagation of electromagnetic wave through it. Thus electromagnetic waves inside cold plasma layer become evanescent. In the light of above facts we can say that the $\omega$ and B dependent feature of $\varepsilon_B$ of cold plasma layer may be very useful in designing of tunable multiple channels of different frequencies to be filtered from photonic structure consisting of magnetic field induced cold plasma layer without defect. Next the transmittance spectra of 1D PPC structure ($AB)^N$ corresponding to $N=2, 3, 4, 5$ and 6 in absence of B at normal incidence $\theta_0 = 0^\circ$ has been plotted in Fig. 3 with the help of Eqs. (1) to (7). Fig. (3) shows $N-1$ number of distinct peaks inside PBG, called as channels in transmission spectra for given $N$.

![Diagram](image.png)

Fig. 3: Transmission spectra of 1D PPC at different value of $N=2, 3, 4, 5$ and 6 showing $N-1$ transmission channels of unit transmittance in the presence of $B = 0.02 T$ under RHP arrangement at and $\theta_0 = 0^\circ$.

For $N = 2$, there exists only one transmission peak of unit transmission located at $f = 4.076 \text{ GHz}$ due to the superposition of evanescent waves (which arises due to forward and backward decaying waves) inside plasma layer and propagating wave inside dielectric layer. This phenomenon is not similar to the formation of transmission band resulting from superposition of forward and backward propagation waves inside dielectric layers [63]. The existence of single transmission peaks of unit transmission in $N = 2$ structure can also be explained on the basis of Fabry Perot cavity nature of structure ($AB)^2$ as BAB by neglecting the first layer of dielectric material A. The appearance of more than one transmission peak corresponding to structures of periods; $N = 3$ to $N = 6$ is due to the quasi Fabry-Perot cavity (FPC) nature of the structures i.e. a structure in which more than one Fabry-Perot cavities are cascaded together. In such cavities the total number of transmission peak are equal to the number of Fabry-Perot cavities.
cascaded together. For example $N = 6$ period 1D PPC (AB)$^6$ can be treated as quasi Fabry Perot cavity of the form $\frac{B A}{2} \frac{B}{2} A \frac{B}{2} A \frac{B}{2} A$. Since this quasi Fabry-Perot cavity is formed by cascading five cavities, the total number of transmission channels would be five. The similar explanation can also be applied over other structures of periods $N = 3$ to 5. Fig. 3 also indicates that for even values of $N$, increase in the number of periods results corresponding increase in number of transmission channels without affecting the central transmission channel located at 4.076 GHz which is common for all even values of $N$. On the other hand the central transmission channel located at 4.076 GHz is absent for all odd values of $N$. There is one more common observation that the increase in the number of periods causes the decrease in the full width at half maxima (FWHM) of each channel of unit transmission i.e. transmission peaks get narrower. Larger the value of $N$ more will be the $N-1$ transmission channels which are so close to form band pass filters.

Fig. 4: Transmission spectra of 1D PPC with $N = 2$ and $\theta_0 = 0^0$ at different magnetic field values of 0T, 0.02T, 0.04T and 0.06T shown by solid line curve of colors blue, red, purple and green respectively under (a) RHP and (b) LHP arrangements.

Next we study the transmission properties of the proposed design with $N = 2$ periods under different values of $B$ which varies from 0 T to 0.06 T in steps of 0.02 under RHP and LHP configuration both at normal incidence as represented in Fig. 4. It can be further noticed that under RHP arrangement, as $B$ increases, the transmission channels shift toward higher frequency side and also transmission channels become narrower as shown in Fig. 4(a). However, mirror image behavior has been observed when the $B$ is applied opposite to the positive direction of z axis as evident in Fig. 4(b). Thus the application of $B$ under RHP and LHP arrangements at normal incidence can be used to change the position of transmission channels both ways as well as it is also used to control the FWHM of each transmission channels. This additional control on FWHM of each transmission channel may be utilized to control the data carrying capacity of associated channel. In addition, the separation between the transmission channels is almost same under the effect of $B$ in RHP and LHP both configurations. Under the effect of $B$ in LHP configuration all transmission channels have unit transmission whereas in RHP configuration transmittance is marginally reduced. In addition to all above mentioned properties the structure with period number more than two possess an additional property by which the separation between adjacent transmission channels can be either decrease with blue shift or increase with red shift under the influence of $B$ in RHP and LHP arrangements respectively. These results are shown in Fig. 5 corresponding to $N = 3$ under the different values of $B$ which varies from 0 T to 0.06 T in steps of 0.02 under RHP and LHP arrangements both.
Fig. 5: Transmission spectra of 1D PPC with $N = 3$ and $\theta_0 = 0^\circ$ at different values of $B$ equal to $0T$, $0.02T$, $0.04T$ and $0.06T$ under (a) RHP and (b) LHP arrangements.

Finally we studied how the change in incident angle $\theta_0$ affects the central frequency of respective transmission channels. For this purpose transmission spectra of the structure corresponding to period number $N$ equal to 2 at the magnetic field value of $0.02T$ under RHP configuration corresponding to four different values of incident angles of as $0^\circ$, $20^\circ$, $40^\circ$ and $50^\circ$ for TE and TM polarizations both have been studied as shown in Figs. 6(a) and 6(b) respectively.
Fig. 6: Transmission spectra of 1D PPC with N = 2 and B = 0.02T under RHP arrangement at different values of incident angle $\theta_0 = 0^0, 20^0, 40^0$ and $50^0$ shown by solid line curves of colours; blue, red, yellow and violet corresponding to (a) TE polarization and (b) TM polarization.

It is evident from the Fig. 6 that as $\theta_0$ increases from $0^0$ to $50^0$ the central frequency of each transmission channel for s- and p- polarized wave both shifted to higher frequency side. In comparison to TE and TM polarizations the shifting is more prominent in TE polarization at $B$ equal to 0.02 T under RHP arrangement. Besides this the transmission channel corresponding to TE polarization gets narrower
as $\theta_0$ increases whereas this feature is missing in case of TM polarization. Further the transmission spectra of the structure corresponding to period number $2$ at magnetic field value of $0.02$ T under LHP arrangement corresponding to different values of $\theta_0$ equal to $0^\circ$, $20^\circ$, $40^\circ$ and $50^\circ$ for TE and TM polarizations both have also been investigated in Fig. 7. Fig. 7(a) exhibits that any increase in $\theta_0$ for TE polarization case results the repositioning of transmission channel towards higher frequency side with decrease in the FWHM of each transmission channel at $B = 0.02$ T under LHP arrangement. These findings are similar to the observations found in Fig. 6(a).

![Graph A](image1)

![Graph B](image2)

Fig. 7: Transmission spectra of 1D PPC with $N = 2$ and $B = 0.02$T under LHP configuration at different values of incident angle $\theta_0 = 0^\circ$, $20^\circ$, $40^\circ$ and $50^\circ$ shown by solid line curves of colours; blue, red, yellow and violet corresponding to (a) TE polarization and (b) TM polarization.
On the other hand the transmission spectra corresponding to TM polarization at fixed value of magnetic field of 0.02 T under LHP arrangement shows very minute impact on change in the position of transmission channel due to increase in the angle of incidence. This feature may be useful for dense division multiplexing in microwave region. Thus the application of $B$ applied externally on 1D PPC consisting of cold plasma layer may provide an additional degree of freedom to design tunable multichannel filters of distinguished features which cannot be obtained by the means of conventional tuning approach like tuning by changing incident angle in microwave regions.

Conclusion

Here we conclude our theoretical findings of multiple transmission channels which can be guided either side of its position by means of an external magnetic field under RHP and LHP arrangements. The standard transfer matrix method has been explored to carry out numerical simulations based on MATLAB. The proposed research work can be employed to reposition the multiple transmission channels swiftly at desired frequency inside PBG externally without disturbing the experimental arrangements of the design. The external presence of $B$ under RHP and LHP arrangements has a significant impact on $\varepsilon_B$ of cold plasma material layer such that transmission channel frequency can be shifted to higher and lower frequency sides both. Thus we can conclude that the $\omega$ and $B$ dependent feature of $\varepsilon_B$ of cold plasma material layer can be utilized to design 1D PPC based tunable multichannel filter consisting of magnetized cold plasma layer without defect which may be very useful in microwave engineering applications. Apart from the application of $B$ under RHP and LHP arrangements the transmission channel can also be guided either side of its position by changing the incident angle corresponding to TE and TM polarization separately. We have also investigated how variation in number of periods $N$ alters the $N-1$ number of distinct transmission channels of unit transmission in microwave frequency region. For large values of $N$ there are more numbers of $N-1$ transmission channels which are so close to form band pass filters. This study also provides an insight how to control FWHM of each transmission channel to control the data carrying capacity of associated channel which may strengthen the data load on network.

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