Design of Cold Plasma Based Ternary Photonic Crystal for Microwave Applications

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Abstract
In this paper, we propose a 1D ternary photonic crystal with Silicon/MCP/Air structure, whose transmission properties have been analyzed. By employing the TMM, the transmittance spectra are plotted for the introduced TPC in four cases by varying the parameters: angle of incidence, lattice constant, static magnetic field, and electron density. The focus of this analysis is to illustrate the PBGs or zero-transmission regions (GHz) exhibited by the TPC in these four cases. In the first case, there exist three PBGs at normal incidence in which the first two bands are enhanced with increase in the incident angle, while the third band shows reverse nature. At the incident angle 89°, three sets of multiple sharp peaks of transmission, showing multichannel filter characteristics, occur in place of allowed regions, and such abnormal feature of the TPC is attributed to the existence of MCP. Next it is demonstrated that such TPC can be exploited as multiband reflectors for a larger lattice parameter with increased thickness of the Si layer. In the third and fourth cases, the first bandgap is found to be least sensitive to the variations in the parameters, while the tunability in second and third bands in both cases is opposite to each other. By comparing the features of this TPC with a binary PC of Silicon/MCP structure, the tunability in the second bandgap is far better in case of TPC. Based on the investigated results, the TPC under different conditions may be a good candidate for various applications, including highly tunable broadband and multiband reflectors; and multichannel filters for dense wavelength division multiplexing and high-speed signal processing.

Keywords Silicon · Cold plasma · Ternary · Transmittance · Oblique · Tunability

1 Introduction
In recent decades, the field of photonic crystal (PC) research has grown exponentially and made a substantial progress. The PCs unprecedentedly enable manipulation and control of the propagation of light, by prohibiting some frequency ranges to propagate through them called photonic bangaps (PBGs), and have emerged as an influential sphere of research [1, 2]. A one-dimensional (1D) PC is usually a class of simplest periodic composite materials with high refractive index contrast exhibiting features of Bragg’s reflection, and is easier to fabricate. The focus of research has been extensively centered on the binary PC and propagation characteristics of such PCs have been analyzed with and without introduced designed defects. To achieve the tunable PC characteristics, the investigations were carried out on the dispersive media, such as semiconductor, plasma, superconductor, liquid crystal, etc., and such PCs with these novel materials have globally generated a great deal of attention by offering reduction in damping of the electromagnetic waves [3–10].
A plasma photonic crystal (PPC) is an artificial periodic array of alternating thin films of un-magnetized or magnetized plasma and a dielectric material or vacuum as the second layer [2]. The PBGs offered by a PPC can be controlled by means of the plasma parameters, like electron density and collision frequency. Among PPCs, a magnetized cold plasma based PC offers an additional parameter called gyro-effective frequency under a magnetic field that depends on the external magnetic field influencing magnetization in the cold plasma. There are two types of polarization configurations, namely right-hand and left-hand polarizations; which occur with positive and negative values of the periodic magnetic field, respectively [11–17]. Cold plasma is generally enough cool and it is
being exploited for several applications in the field of power production, and can support a large number of chemical reactions [11, 12]. Kumar et al. [2, 18] reported the variations in photonic band structures (PBSs) as a function of variable parameters, viz. angle of incidence, magnetic field, electron density, and layer thickness; for TE and TM modes.

Furthermore, the focus of PC research is being shifted toward ternary photonic crystal (TPC), which has nowadays many applications in the fields of optical engineering and optical communication [2]. The ternary structures with a variety of materials are being investigated for novel and efficient kinds of tunability in their PBGs and providing better performance in device based applications as compared to a binary PC [19–25]. Among them, Abadla et al. [22] reported the temperature sensor based application of a ternary PC; and in more recent works, Abihoassan et al. [23] have analyzed a TPC and shown its application as a wide angle infrared reflector.

Motivated by a multitude of advantages offered by TPC, we decided to work on magnetized cold plasma (MCP) based 1DTPC by introducing Silicon/MCP/Air as a ternary periodic PC structure, and its transmission properties have been investigated. In this simulation work, we mainly concentrate on the PBGs or zero-transmission regions exhibited by the TPC in various cases with varying the four parameters: incident angle, lattice constant, magnetic field, and electron density. Here, it is shown that such a ternary PC has higher number of bands for smaller angles, which makes it a good candidate for multiband reflectors and at higher angles, it behaves like broadband reflectors. Moreover, the transmission characteristics of the ternary PC are compared with those of a binary PC having Si/MCP periodic structure by keeping the lattice constant same, and the advantages of TPC over binary PC are discussed.

As per the knowledge of the investigators, the introduced structures with specified materials have not been studied so far. Although based on different techniques the ternary structures have been theoretically as well as experimentally shown to be useful for tunable band based applications [24, 25], the introduced Si and MCP based binary and ternary periodic composite structures are analyzed using the transfer matrix method, in order to obtain the desired tunable band applications with the proposed ternary PC structure.

Thus, the manuscript presents a detailed exploration of the transmission properties of the introduced TPC, and highlights the implications of the contributing results in designing microwave devices. This paper is organized in the following manner: Section 2 covers the TPC structure and the method to be employed, Section 3 elaborates the Results and Discussion, and Section 4 presents the Conclusion.

2 Theoretical Modeling

In this analysis, we consider a one-dimensional ternary PC structure made of periodic arrangement of three consecutive layers, that is, silicon (semiconductor), magnetized cold plasma, and air. The TPC under consideration is as shown in Fig. 1, where the propagation is assumed to be along z-direction. The refractive indices of Si, MCP and air are denoted by \( n_1, n_2 \) and \( n_3 \), respectively. Here, it is assumed that the MCP layer is under right-hand polarization (RHP), where the direction of static magnetic field is along the propagation z-direction. The three layers make a unit cell, and we have taken \( N \) number of unit cells for the ternary periodic PC structure in the form \((ABC)^N\), where A, B and C are the Si, MCP and air layers, respectively. The layer thicknesses are represented as \( d_1, d_2 \) and \( d_3 \), for Si, MCP and air, respectively. The thickness of the unit cell is \( d = d_1 + d_2 + d_3 \), which is known as lattice constant.

The transmittance spectra of this TPC are theoretically determined by using the famous transfer matrix method (TMM), a well-known method used for calculating the reflectance and transmittance through a layered media [26–30]. In TMM, the total characteristic matrix for the structure \((ABC)^N\) with \( N \) periods, is expressed as [26, 29].

\[
M(\alpha d) = \begin{bmatrix}
m_{11} & m_{12} \\
m_{21} & m_{22}
\end{bmatrix},
\]

The total matrix can be written by introducing the characteristic matrix for each layer, which is given for the \( k \)th layer as [26–28].

\[
M_k = \begin{bmatrix}
\cos \gamma_k & -i \alpha_k \sin \gamma_k \\
i \alpha_k \sin \gamma_k & \cos \gamma_k
\end{bmatrix},
\]

where \( i = \sqrt{-1} \), \( \gamma_k = \left( \frac{\pi}{\lambda_0} \right) n_k d_k \cos \theta_k \), \( c \) represents the speed of light in vacuum, \( \theta_k \) is the ray angle in the \( k \)th layer (\( k = 1, 2 \) and 3; viz. A, B and C materials), and the refractive index of the \( k \)th material is \( n_k = \sqrt{\mu_k \epsilon_k} \). For the transverse electric (TE) mode, we define a parameter \( \alpha_k = \sqrt{\frac{\mu_k \epsilon_k}{\lambda_0} \cos \theta_k} \), where \( \cos \theta_k = \sqrt{1 - \frac{n_k^2 \sin^2 \theta_k}{n_i^2}} \), \( \theta_i \) is the angle of incidence from air to the axis of the layered media, and the refractive index of air as the incident medium is taken as \( n_0 \). Here, \( M_A, M_B \) and \( M_C \) are the characteristic matrices for the three layers A, B and C, viz. Si, MCP and air, respectively; and can be written with the help of Eq. (2). Thus, total characteristics matrix will be \( M(\alpha d) = \left( M(d) \right)^N = \left[ M_A, M_B, M_C \right]^N \).

Hence, the transmission coefficient of a TPC, which is in the form of \((ABC)^N\), is expressed as [28–30].
\[ t = \left( \frac{2\alpha_i}{m_1 + m_{12}\alpha_s} \right) \frac{1}{\alpha_i + (m_{21} + m_{22}\alpha_s)} \]  

(3)

where \( \alpha_i = n_0 \cos \theta_i \) and \( \alpha_s = n_s \cos \theta_s \) with \( \mu_i = \mu_s = 1 \), for air; \( n_s \) is the refractive index of the substrate, and \( \theta \) is the emergence angle in the substrate that is also assumed to be air, and hence \( n_1 = n_s = n_0 \). Here, the transmittance \( T \) for 1D ternary periodic structure is given by [23, 27, 29].

\[ T = \frac{\alpha_s}{\alpha_i} |t|^2. \]  

(4)

The complex permittivity of the cold plasma in a static magnetic field \( B \) is a function frequency \( (\omega) \), and it is expressed as [14, 30].

\[ \varepsilon_2 = 1 - \frac{\omega_{pe}^2}{\omega^2} \left[ 1 - \frac{\zeta}{\omega} + \frac{\omega_{pe}}{\omega} \right] \]  

(5)

where gyro-frequency is \( \omega_{pe} = \frac{eB}{m} \), and the -ve sign before \( \omega_{pe} \) indicates the positive value of the magnetic field along the propagation direction for the RHP configuration. Here, \( \zeta \) represents the effective collision frequency, and plasma frequency is given by \( \omega_{pe} = \sqrt{\frac{\varepsilon_0 n_e}{m_e}} \); where \( m, n_e, \varepsilon_0, B \) and \( e \) are the electronic mass, electron density, permittivity in free-space, static magnetic field, and the electronic charge, respectively.

Hence, we determine the transmittance spectra using Eq. (4) in four cases with variations in the parameters like, incident angle, lattice constant, static magnetic field, and electron density. We compare these transmission spectra obtained in various cases and investigate the impacts of these parameters on the transmittance, mainly on the PBG regions with zero-transmission.

3 Results and Discussion

In this section, we determine the transmittance characteristics of a 1DTPC based on the four parameters, viz. incident angle \( \theta_i \), lattice parameter \( d \), static magnetic field \( B \), and electron density \( n_e \) for specified values of effective collision frequency \( \zeta \), and the number of lattice periods \( N \). All the parameters are chosen as follows: The refractive indices of Si, MCP and air are taken as: \( n_1 = 3.46, n_2 = \sqrt{\varepsilon_2} \) and \( n_3 = 1 \), respectively; the two parameters \( \zeta \) and \( N \) are fixed in the whole investigation as: \( \zeta = 2\pi \times 10^7 \) Hz, and \( N = 10 \). The transmittance \( (T) \) versus frequency \( (\nu) \) spectra, of the proposed TPC in the range 1–10 GHz, are plotted using TMM. In this comparative analysis, we emphasize on the effects of variations in four different parameters, such as \( \theta_i, d, B, \) and \( n_e \), on the PBGs obtained in four different cases.

In the first case, the transmittance spectra are drawn for the TPC considering \( n_e = 8 \times 10^{17} \) per m\(^3\), \( B = 1.5 \) T, \( d = 30 \) mm with \( d_1 = d_3 = d_3 = 10 \) mm. Here, angle of incidence is varied as: \( \theta_i = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, \) and \( 89^\circ \); keeping the rest parameters constant. The transmittance spectra so obtained are illustrated in Fig. 2a-g. Now, we observe the zero-transmission frequency ranges called PBGs, and the obtained results are listed in Table 1.

From Fig. 2, it is observed that, there exist three complete bandgaps at normal incidence and with increase in incident angle from \( 0^\circ \) to \( 45^\circ \), the first two bandgaps are showing broad-band effects and are enhanced, while the third bandgap shows peculiar nature and almost decreases, and on further increasing the angle of incidence, the complete band of third PBG does not exist in the frequency range (1–10 GHz). Hence, one can mention that an increase in incident angle decreases the number of bands. Here, at incident angle above \( 45^\circ \), the second band becomes wider as compared to first one for a given value of the incident angle, and so we can say that the second bandgap is more tunable and becomes prominent as compared to the first bandgap. It also is noted that the upper band edges of the two PBGs are shifted towards a higher value of frequency, where the lower band edges are least affected. Therefore, it is inferred that there is less impact of the incident angle on the first bandgap as compared to second; while there
is a reverse effect on the third PBG, whose width decreases with increase in incident angle, and the complete band does not exist beyond 45°, as clearly mentioned Table 1. It is also found from Table 1 that the second band is comparatively more tunable as compared to the first bandgap.

Overall, we demonstrate that the impact of increasing incident angle is to tune the widths of forbidden gaps and the number of bands. The proposed PC with such characteristics exhibits better capabilities to be a good multiband reflector at smaller angles and at higher angles it offers a novel idea in designing tunable broadband reflectors and optical mirrors in the microwave region. When the value of incident angle is increased to 89°, the two bandgaps become maximum, while in the complete zero-transmittance region, three sets of transmittance peaks are observed showing the multichannel filter characteristics, while the first set of such peaks have transmittance below 0.5. Such feature of TPC is attributed to the presence of magnetized cold plasma in the structure.

As it has been already reported in the case of MCP that at a lower frequency, more damping in TE waves appears and so transmission decreases, while its effect is less at higher frequency regime [16]. Therefore, the first sets of transmission peaks bear least transmittance below 0.5. Such sharp peaks (channel) usually exist in binary and ternary PCs, when metamaterials are introduced in the structures [31, 32]. Here, we have used the MCP whose complex dielectric constant is frequency dependent, and so the dielectric constant may exhibit anomalous behaviors in certain frequency regions with specific plasma parameters. Such multichannel filtering characteristics of the TPC at incident angle 89° may find potential applications in dense wavelength division multiplexing and ultrafast light signal processing systems [31].

In the second case of the analysis, we determine the effect of the lattice parameter on the transmittance spectra, at normal incidence θ_i = 0°, and calculate the corresponding PBGs by considering: \( n_e = 8 \times 10^{17} \text{ per m}^3 \) and \( B = 1.5 \text{ T} \), with variation in \( d \), that is, \( d_1 \) by keeping \( d_2 = d_3 = 10 \text{ mm} \). Here, the width of Si layer is varied as: \( d_1 = 10 \text{ mm}, 15 \text{ mm}, 20 \text{ mm}, 25 \text{ mm}, 30 \text{ mm}, \) and \( 35 \text{ mm} \), and the transmittance spectra are plotted and are shown in Fig. 3a-f; and we again focus on the zero-transmission frequency ranges called PBGs. By comparing the obtained spectra in various cases of the Si layer thickness, we find that, as we increase the silicon thickness from 10 mm to 35 mm, the number of bands increases from 3 to 7.

Hence, we can say that such a TPC can be used as microwave multiband reflectors for a larger width of the lattice parameter, where the thicknesses of MCP and air are kept constant.

Referring to the third case, we investigate the effect of the magnetizing field \( B \) on the transmittance spectra of the TPC and the corresponding PBGs at normal incidence \( \theta_i = 0° \), by considering \( n_e = 8 \times 10^{17} \text{ per m}^3 \) and \( d = 30 \text{ mm} \) (with \( d_1 = d_2 = d_3 = 10 \text{ mm} \)). In this case, the magnetic field is changed as: \( B = 0.7 \text{ T}, 0.9 \text{ T}, 1.1 \text{ T}, 1.3 \text{ T}, 1.5 \text{ T}, \) and \( 1.7 \text{ T} \), and the obtained spectra have been depicted in Fig. 4a-f. By making comparison of these spectra, we infer that, there lie three bandgaps, where third bandwidth is very small and first gap is widest. With increase in the magnetic field, the second band becomes wider and third band becomes narrower, and all bands get saturated both in number as well as thickness at \( B = 1.1 \text{ T} \) or above, where the first bandgap is very less sensitive to the magnetizing field. Based on the comparative results, the lower edges of all bands are less sensitive to the magnetic field, while upper band edge of second gap is considerably more sensitive than that of the first and third bandgaps and is shifted to higher frequency with an increase in the magnetic field. In this observation, the key point is that the first bandgap is the wider than second and third bands, where the mid frequency and bandwidth of the first bandgap are least sensitive to the applied magnetic field.

In the fourth case, we research on the impact of the electron density on the transmittance spectra of the TPC, at normal incidence \( \theta_i = 0° \), and the corresponding PBGs are determined by considering, \( B = 1.5 \text{ T} \) and \( d = 30 \text{ mm} \) (with \( d_1 = d_2 = d_3 = 10 \text{ mm} \)). Here, the electron density \( n_e \) is varied as: \( n_e = 6 \times 10^{17}/\text{m}^3, 8 \times 10^{17}/\text{m}^3, 10 \times 10^{17}/\text{m}^3, 12 \times 10^{17}/\text{m}^3, 14 \times 10^{17}/\text{m}^3, \) and \( 16 \times 10^{17}/\text{m}^3 \); and the obtained spectra have been depicted in Fig. 5a-f. On comparison of these

| Incident Angle (θi) | First PBG (GHz) | Second PBG (GHz) | Third PBG (GHz) |
|---------------------|-----------------|-----------------|-----------------|
|                     | Range           | Bandwidth       | Range           | Bandwidth       | Range           | Bandwidth       |
| 0°                  | 1.740–3.440     | 1.700           | 4.795–6.045     | 1.250           | 7.605–8.420     | 0.815           |
| 15°                 | 1.745–3.490     | 1.745           | 4.805–6.180     | 1.375           | 7.755–8.445     | 0.690           |
| 30°                 | 1.765–3.635     | 1.870           | 4.895–6.595     | 1.700           | 8.295–8.555     | 0.260           |
| 45°                 | 1.785–3.860     | 2.075           | 4.995–7.295     | 2.300           | 9.030–9.380     | 0.350           |
| 60°                 | 1.815–4.085     | 2.270           | 5.115–8.115     | 3.000           | __              | __              |
| 75°                 | 1.835–4.270     | 2.435           | 5.215–8.665     | 3.450           | __              | __              |
| 89°                 | 1.740–4.345     | 2.605           | 5.090–8.850     | 3.760           | __              | __              |
spectra, we investigate that, there exist three bandgaps, where the first bandwidth is widest almost independent of the variation in electron density. With increase in the electron density, the second band becomes narrow and third band is
enhanced. Hence, we can report that the first bandgap is the wider than second and third tunable bands. By increasing the electron density the bandwidth of second band is decreasing and third band is increasing, whereas lower end of second and upper edge of third bands show less sensitive behaviors to the electron density variation.

Fig. 3 Transmittance spectra of the TPC at normal incidence with $B = 1.5 \, \text{T}$ for: a $d_1 = 10 \, \text{mm}$, b $d_1 = 15 \, \text{mm}$, c $d_1 = 20 \, \text{mm}$, d $d_1 = 25 \, \text{mm}$, e $d_1 = 30 \, \text{mm}$ and f $d_1 = 35 \, \text{mm}$
In addition, in order to see the advantages of the ternary PC, we make a comparison between the impacts of incident angle on the ternary PC and a proposed binary PC with Silicon/MCP structure, by ignoring the third layer of air and keeping the same lattice constant $d$. For this binary PC, the transmittances are calculated by choosing the same values of the parameters as taken in case I for the ternary PC, that is, $n_e = 8 \times 10^{17}$ per m$^3$, $\zeta = 2\pi \times 10^7$ Hz, $B = 1.5$ T, $N = 10$, and $d = 30$ mm.

Fig. 4 Transmittance spectra of the TPC at normal incidence with $d = 30$ mm for: (a) $B = 0.7$ T, (b) $B = 0.9$ T, (c) $B = 1.1$ T, (d) $B = 1.3$ T, (e) $B = 1.5$ T, and (f) $B = 1.7$ T.
(with $d_1 = d_2 = 15 \text{ mm}$). Here, angle of incidence is varied as: $\theta_i = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ$, and $89^\circ$; and the transmittance spectra are shown in Fig. 6a-g, and the results so obtained are listed in Table 2.

On comparing these transmittance spectra, as we found that the TPC offers three photonic bandgaps at lower angles $0^\circ$ to $45^\circ$, while in binary case we have three bands for all angles even four at incident angle $30^\circ$, and the second band is wider.
as compared to the first one for a given value of the incident angle. The basic difference is the existence of three bands at higher incident angles in binary PC, which did not exist in ternary above the incident angle 45°. Moreover, in the ternary PC, the first gap was wider than the second up to incident angle 30°, while there is reverse feature in binary PC. Also, in binary PC all the bandgaps are increasing with increase in the incident angle showing the nature of Bragg’s reflection, where the second and third gaps are more influenced by the incident angle. Besides this, referring to Table 2, we find that the third band of binary PC shows better tunability in its width as compared to its second band. Thus, it is to note that binary PC has larger number of photonic bandgaps than TPC. Again, the existence of four sets of transmittance peaks, in zero-transmittance region of binary PC at the incident angle 89°, is owing to the presence of MCP with complex dielectric constant; and it is considered as a revolutionary feature of such PCs made of periodic composites of Si and MCP.

From Table 1, it was inferred that the second band of ternary PC is highly tunable as compared to its first band, where third band shows peculiar nature. Therefore, for the sake of common basis of comparison, we concentrate on the tunability in bandwidths of the second forbidden band for binary and ternary PCs against incident angle as illustrated in Fig. 7. Although the second bandwidth of the binary PC increases with an increase in the incident angle, the increase is minor as compared to that of the ternary PC. For the second bandgap at angle of incidence between 0° to 15°, the binary PC offers larger bandgap width as compared to TPC. However, it is noted that the bandwidth of ternary PC is more tunable than that of binary above the incident angle 15°; and shows a considerable monotonic increase in the bandwidth with increase in incident angle, and consequently leads over that of binary. From the above research results, it is revealed that the ternary PC is more sensitive to the variation in the angle of incidence as compared to binary. This feature may be considered as an advantage of ternary PC over binary. Here, at incident angle 89°, there exist four sets of transmittance sharp peaks in place of allowed regions, which were only three in the case of TPC. Hence, both types of PCs show multichannel filtering behaviors at the incident angle 89°. Hence, we demonstrate that TPC has highly tunable second bandgap, and it behaves like wideband reflectors in a low frequency regime, whereas the binary PC can be operated in the high frequency region for better bandgap tunability and broadband reflector characteristics.

### 4 Conclusion

In this work, cold plasma based ternary photonic crystal with Silicon/MCP/Air periodic structure, is presented. With the help of the TMM, the transmittance spectra are drawn for the TPC in four cases by varying the internal as well as external parameters; angle of incidence, lattice constant, static magnetic field, and electron density; and the focus of attention is on zero-transmittance bands, i.e., PBGs offered by the TPC in the range 1–10 GHz. It is observed in the first case that there exist three PBGs in which the first two are forbidden bands get enlarged with an increase in the incident angle, where the second photonic bandgap is highly affected. The third bandgap shows reverse nature, whose complete band does not exist in the range for the incident angle above 45°. At the incident angle 89°, three sets of multiple sharp peaks of transmission, showing multichannel filter like features, are obtained in place of allowed regions, and the two bandgap widths achieve the maximum values. Such feature of exhibiting sharp peaks by the TPC in the complete zero-transmission region is attributed to the existence of MCP. Hence, the TPC exhibits the features of multiband reflectors at smaller angles, whereas it acts like broadband reflectors as well as multichannel filters at higher angles. For the second parameter, we state that, such a TPC can be used as microwave multiband reflectors for a larger width of the lattice parameter due to increased thickness of Si layer. In the third and fourth cases with variations in the static magnetic field and electron density, respectively; it is noted that the first bandgap is the prominent one as compared to second and third

| Incident Angle (°) | First PBG (GHz) Range | Bandwidth | Second PBG (GHz) Range | Bandwidth | Third PBG (GHz) Range | Bandwidth |
|-------------------|-----------------------|-----------|------------------------|-----------|-----------------------|-----------|
| 0°                | 1.545–2.520           | 0.975     | 3.625–5.025            | 1.400     | 6.090–7.205           | 1.115     |
| 15°               | 1.550–2.540           | 0.990     | 3.665–5.070            | 1.405     | 6.135–7.305           | 1.170     |
| 30°               | 1.565–2.575           | 1.010     | 3.685–5.230            | 1.545     | 6.210–7.600           | 1.390     |
| 45°               | 1.580–2.655           | 1.075     | 3.735–5.495            | 1.760     | 6.310–8.030           | 1.720     |
| 60°               | 1.595–2.705           | 1.110     | 3.790–5.635            | 1.845     | 6.415–8.460           | 2.045     |
| 75°               | 1.605–2.805           | 1.200     | 3.835–5.795            | 1.960     | 6.495–8.750           | 2.255     |
| 89°               | 1.500–2.835           | 1.335     | 3.780–5.870            | 2.090     | 6.480–8.815           | 2.335     |
bands, and its mid frequency as well as bandgap is least sensitive to the variations in the applied static field and electron density. Here, on the basis of comparison for these two parameters, it is reported that the tunability in second and third bandgaps in both cases are opposite in to each other. On increasing the magnetic field, the second PBG becomes enlarged, whereas increase in the electron density increases the third PBG, while in both cases the impacts of these parameters are very less.

**Fig. 6** Transmittance spectra of a binary PC with lattice constant $d = 30$ mm and $B = 1.5$ T at: a $\theta = 0^\circ$, b $\theta = 15^\circ$, c $\theta = 30^\circ$, d $\theta = 45^\circ$, e $\theta = 60^\circ$, f $\theta = 75^\circ$, and g $\theta = 89^\circ$
In addition, on comparing this ternary PC with a binary PC of Si/MCP structure with same value of the lattice parameter, it can be clearly seen that, such TPC can act as a good reflector and provides better tunable band characteristics in the low frequency regime, while binary PC can be operated in the high frequency regime for the similar features. For the incident angle above 15°, the second forbidden gap of TPC is more tunable than binary PC with respect to variation in the incident angle.

Overall, this paper sheds light on exploring the transmission characteristics of the proposed TPC. Based on the comparative research results in various cases of impacts of the aforesaid four parameters, it is demonstrated that the introduced TPC can be useful for several applications, including ultrahigh tunable multiband and broadband reflectors, switching applications, other similar microwave devices, and multichannel filters for designing dense wavelength division multiplexing and high speed signal processing systems. This comparative analysis for the introduced ternary PC can be further employed for making modeling of related ternary PCs by introducing designed defects.

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