Chapter 3
Dielectric-Plasma
Photonic Band Gap
Materials
3.1 Introduction

A wide variety of macroscopically neutral substances containing many interacting free electrons and ionized atoms or molecules, which exhibit collective behaviour due to long-range coulombic forces are called plasma. For a collection of interacting charged particles and neutral particles to exhibit plasma behaviour, it must satisfy certain conditions or criteria, for plasma existence. The word plasma comes from the Greek word which means “Something molded”. In 1929, for the first time, Tonks and Langmuir [1] described a glowing ionized gas produced by electrical discharge in a tube, as plasma yet the ionized gas as a whole remaining electrically neutral. We know that when a solid or liquid substance is heated the atoms or molecule of substances acquire more thermal kinetic energy, and they may be able to overcome the binding potential energy at some stage or temperature. This leads to “Phase-transition”, which occurs at a constant temperature for a given pressure. The amount of energy required for the phase transition is called the latent heat. If sufficient energy is provided to substances, a molecular gas will gradually dissociate into an atomic gas as a result of collision among constituent particles when the thermal kinetic energy exceeds the molecular binding energy. At sufficiently elevated temperatures, an increasing fraction of the atom will possess enough kinetic energy to overcome, by collisions, the binding energy of the outermost orbital electrons and an ionized gas or plasma results. However, this
transition from a gas to plasma is not a phase transition in the thermodynamic sense, since it occurs gradually with increasing temperature [2,3].

An important plasma property is the stability of its macroscopic space charge neutrality. When plasma is instantaneously disturbed from the equilibrium condition, the resulting internal space charge fields give rise to collective particle motions which tend to restore the original charge neutrality. These collective motions are characterized by a natural frequency. The angular frequency of the collective electron oscillation, called the plasma oscillation frequency, is given by \( \omega_p = (n_p e^2/m \varepsilon_0)^{1/2} \). Collisions between electrons and neutral particles tend to damp these collective oscillations and gradually diminish their amplitudes. If the oscillations are to be only slightly damped, it is necessary that the electron-neutral particle collision frequency, \( \nu_n \), be smaller than the electron plasma frequency, i.e. \( \nu_p ( = \omega_p / 2 \pi ) > \nu_n \).

Photonic crystals, which are known to exhibit many unique features, have been gaining attention in the field of solid state and optical physics [4,5]. The technological applications of photonic crystals are expanding widely. For the first time, Keskinen and Fernsler [6] and Hojo and Mase [7] have studied photonic band gaps in photonic crystals using dusty plasma and discharged micro-plasma respectively that is named as Plasma Photonic Crystal (PPC). Plasma photonic crystal is a periodic array composed of alternating layers of plasma and dielectric materials. Hojo and Mase studied plasma photonic crystal and showed that photonic band gap(s) increase as we increase the width of plasma layer as well as the plasma density. It is also confirmed by Ojha et al. [8].
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The periodic structure of dielectric materials i.e. photonic band gap (PBGs) materials have attracted much interest in the field of solid state and optical physics [2,4]. Plasma photonic crystals are one-, two- and three-dimensional periodic structure having spatially and dynamically controlled micro-plasma that play a significant role in changing the refraction of electromagnetic waves through the composite structure, whereas conventional photonic crystals are composed of solid materials including dielectrics, metals etc. The unique characteristics of photonic crystals like band gaps and negative refraction, which cannot be accomplished in bulk materials have been reported in the case of dielectric photonic crystals [9,10]. By replacing solid materials with “plasma” two important features are added to usual photonic crystals:

1. Dynamical (time-varying) controllability.

2. Strong dispersion around the electron plasma frequency.

These facts will lead to the development of dynamic and functional devices to electromagnetic waves ranging from microwaves to THz waves, according to the scale and the electron density of plasma. Keskinen and Fernsler [6] have theoretically studied photonic band gaps in dusty plasma crystals. Dusty plasma has been much of interest due to the dynamic structure and general phenomenology. In space, dusty plasma can be found in accretion disks, supernova remnants, interstellar clouds etc. The structure of dielectric dusty plasma crystals can be one-, two- and three-dimensional and contain face centered cubic (fcc), body central cubic (bcc) and other symmetries. Several aspects of dusty plasma crystals have been studied so far [11-13]. Using plane wave expansion techniques, the electromagnetic wave propagation in a dusty plasma crystal is found to have many regions of wavelengths for which electromagnetic wave propagation is forbidden,
known as photonic band gaps and when the length scale, known as Debye length, is comparable with respect to the dust particle size. The band gap features are dependent on the plasma sheath characteristics in the case of one-dimensional crystal i.e. the relative size of the particle plus plasma sheath with respect to the lattice constant of the dusty plasma crystal. The effects of the plasma sheath are to increase the widths of forbidden band gaps. In addition, the band gap width is a function of the ratio of the dust dielectric constant with respect to the background plasma. The application of such dusty particle is used to control the electromagnetic energy in plasma processing system and in the development of plasma mirror [14]. Recently quantum electrodynamical effect in dusty plasma is studied by Marklund et al. [15,16]. They predicted a new non-linear electromagnetic wave mode in magnetized dusty plasma. Its existence depends on the interaction of an intense circularly polarized electromagnetic wave within dusty plasma where quantum electro-dynamical photon-photon scattering is taken into account. It could be of significance for the physics of the supernova remnants and in the neutron star formations. On the other hand Hojo and Mase [7] have studied theoretically the band gap structure and reflectionless transmission of electromagnetic wave in one dimensional Plasma Photonic Crystals (PPCs) with alternate layers of micro-plasma and dielectric materials. By solving a Maxwell’s equations using a method analogous to Kroning-Penny’s model in quantum mechanics, the dispersion relation is obtained. The frequency gap and cutoff appeared in the dispersion relation of the PPCs. The band gap is found to become larger with the increase of plasma density as well as plasma width. The reflection less transmission can be possible for single layer transmission as well as for two layers at critical
plasma frequency and this is considered as Fabry-Perot resonance, which is well known in optics [17,18].

In this chapter, the electromagnetic properties of one dimensional dielectric-plasma photonic crystals (PPCs) namely, band structure, reflection properties, group velocity and effective group index have been presented. Here, two structures PPC1 and PPC2 are considered by choosing SiO$_2$ and TiO$_2$ as the materials of dielectric layers of PPC1 and PPC2 respectively because these materials are two commonly used dielectric materials in semiconductor industry.

### 3.2 Theoretical Analysis

We consider one dimensional plasma photonic crystals (PPCs) having alternate layers of dielectric and micro-plasma as shown in Figure 3.1.

![Figure 3.1: Periodic variation of plasma and dielectric showing 1-D plasma photonic crystals.](image)

The dispersion relation, reflectivity, group velocity and effective group index of such one-dimensional plasma photonic crystals (PPCs) are computed using by transfer matrix method [19]. The Maxwell wave equations for electromagnetic wave propagating along the x-axis in one-dimensional PPCs may be written as
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\[
\frac{d^2 E(x)}{dx^2} + k_0^2 \varepsilon(x) E(x) = 0, \tag{3.1}
\]

with \( \varepsilon(x) = \begin{cases} 1 - \frac{\omega_p^2}{2}, & -L_d < x < 0, \\ \varepsilon_m, & 0 < x < L, \end{cases} \tag{3.2} \)

and \( \varepsilon(x) = (x + D), \tag{3.3} \)

where, \( k_0 = \omega / c \) is the wave frequency,
\( c \) is the speed of light,
\( \omega_p = (e^2 n_p / m)^{1/2} \) is the electron plasma frequency with density \( n_p \)
\( \varepsilon_m \) is the dielectric constant of the dielectric material.

The schematic diagram of the spatial variation of micro-plasma and dielectric material is given in Figure 3.1, where \( D = L(1 + d) \) is the lattice period with the widths of dielectric and micro-plasma being \( L \) and \( L_d \) respectively.

The general solution of the equation (3.1) is given by, for \( \omega < \omega_p \)
\[
E(x) = \begin{cases} a_m e^{ik_d x} + b_m e^{ik_p x}, & -L_d < x < 0, \\ c_m e^{ik_m x} + d_m e^{ik_p x}, & 0 < x < L, \end{cases} \tag{3.4}
\]

and for \( \omega > \omega_p \)
\[
E(x) = \begin{cases} a_m e^{ik_d x} + b_m e^{ik_p x}, & -L_d < x < 0, \\ c_m e^{ik_m x} + d_m e^{ik_p x}, & 0 < x < L, \end{cases} \tag{3.5}
\]

where, \( k_d = \omega / (e \tau)^{1/2}, k = \omega / (\varepsilon_m \omega_p^2 / \omega^2 - 1)^{1/2} \) and \( k_p = / (1 - \omega_p^2 / \omega^2)^{1/2} \); and \( a_m, b_m, c_m \) and \( d_m \) are constants.

By imposing the continuity of \( E(x) \) and \( E'(x) \) at the interfaces of different materials of the structures, we obtained the following matrix equation
Here, the translation matrix is given by

$$\begin{bmatrix} a_{m,1} \\ b_{m,1} \end{bmatrix} = M \begin{bmatrix} a_m \\ b_m \end{bmatrix}$$

(3.6)

where the elements of the matrix in Eq. (3.6) are

for \(\omega < \omega_p\)

$$m_1 = e^{ik_d L} \left[ \cosh(\kappa : L \lambda) - \frac{i}{2} \left( \frac{\kappa}{k_d} - \frac{k_d}{\kappa} \right) \sinh(\kappa : L \lambda) \right],$$

(3.8a)

$$m_2 = e^{-ik_d L} \left[ -i \left( \frac{\kappa}{k_d} + \frac{k_d}{\kappa} \right) \sinh(\kappa : L \lambda) \right],$$

(3.8b)

$$m_{11} = e^{ik_d L} \left[ i \left( \frac{\kappa}{k_d} + \frac{k_d}{\kappa} \right) \sinh(\kappa : L \lambda) \right],$$

(3.8c)

$$m_{22} = e^{-ik_d L} \left[ \cosh(\kappa : L \lambda) + \frac{i}{2} \left( \frac{\kappa}{k_d} - \frac{k_d}{\kappa} \right) \sinh(\kappa : L \lambda) \right].$$

(3.8d)

and for \(\omega > \omega_p\)

$$m_1 = e^{ik_d L} \left[ \cos(k_p : L \lambda) + \frac{i}{2} \left( \frac{k_p}{k_d} + \frac{k_d}{k_p} \right) \sin(k_p : L \lambda) \right],$$

(3.9a)

$$m_2 = e^{-ik_d L} \left[ -i \left( \frac{k_p}{k_d} + \frac{k_d}{k_p} \right) \sin(k_p : L \lambda) \right],$$

(3.9b)

$$m_{11} = e^{ik_d L} \left[ -i \left( \frac{k_p}{k_d} + \frac{k_d}{k_p} \right) \sin(k_p : L \lambda) \right],$$

(3.9c)

$$m_{22} = e^{-ik_d L} \left[ \cos(k_p : L \lambda) - \frac{i}{2} \left( \frac{k_p}{k_d} - \frac{k_d}{k_p} \right) \sin(k_p : L \lambda) \right].$$

(3.9d)

Now, because of the periodicity in the structure of the PPCs, the electric field vector can be expressed in the form \(E(x) = E_\kappa(x)e^{ikx}\), (according
to Bloch’s theorem) where $E_K(x)$ is periodic with the lattice period of $D$. The constant $K$ is known as wave number and is given by

$$K(\omega) = \frac{1}{D} \cos \left[ \frac{1}{2} \left( M_{11} + M_{22} \right) \right] \quad (3.10)$$

The solution of equation (3.10) leads to the dispersion relation for the PPC structures containing the alternate layers of dielectric and micro-plasma and it is given by

for $\omega < \omega_p$

$$K(\omega) = \frac{1}{D} \cos \left[ \cos(k_d L) \cosh(k_s L d) + \frac{1}{2} \left( k_s - k_d \right) \sin(k_d L) \sinh(k_s L d) \right] \quad (3.11)$$

for $\omega > \omega_p$

$$K(\omega) = \frac{1}{D} \cos \left[ \cos(k_d L) \cosh(k_s L d) - \frac{1}{2} \left( k_s + k_d \right) \sin(k_d L) \sinh(k_s L d) \right] \quad (3.12)$$

However, the group velocity $[V_g(\omega)]$ can be expressed by using formula $[20]$

$$V_g = \left( \frac{dK}{d\omega} \right)^{-1} \quad (3.13)$$

And the effective group index of refraction $n_{eff}(g)$ can be calculated by using the following formula

$$n_{eff}(g) = \frac{c}{V_g} \quad (3.14)$$

Also, the coefficient of reflectivity of the PPC structure with $N$ unit cells can be calculated by using the following relation $[19]$

$$R_N = -\left( \frac{b_N}{a_0} \right)_{b_N=0} \quad (3.15)$$

where, $a_0$ and $b_0$ are the complex amplitudes of incident and reflected plane waves; and the condition $b_N=0$ implies the boundary condition that to the
right of periodic structure there is electromagnetic plane wave incident on the structure.

By solving the above equation up to the $N^{th}$ power of a unimodular matrix, we find the expressions for the reflectivity of the PPC structure, which is given by

$$|R_n|^2 = \frac{|M_{21}|^2}{|M_{21}|^2 + (\sin(KD)/\sin(NKD))^2}$$

(3.16)

3.3 Results and Discussion

In this section, we compute the band structure, group velocity, $V_g$, effective group index, $n_{eff}(g)$ and reflectivity on the scale of normalized frequency $(\omega L/2\pi c)$ of one-dimensional plasma photonic crystals (PPCs) for both cases for which the frequency of radiation, $(\omega < \omega_P$ and $(\omega > \omega_P)$ where $\omega_P$ is the plasma frequency. In this study, we consider two PPC structures with alternate layers of dielectric and micro-plasma as -

(i) PPC1: SiO$_2$-Plasma
(ii) PPC2: TiO$_2$-Plasma

For both the PPCs, the thickness of plasma layer is taken as $Ld$ with plasma frequency $5.6 \times 10^{11}$Hz. The thickness of dielectric layer is taken as $L$ with refractive index 1.5 for SiO$_2$ (in PPC1) and 2.3 for TiO$_2$ (in PPC2). Two cases of different thickness ratios ($Ld/L=d$) for both the structures are considered for which the ratios are 0.01 and 0.10 for the PPC1 and PPC2 respectively.
3.3.1 Case I: \( d \leq P \)

The band structure of one-dimensional PPCs, in terms of normalized frequency and wave vector obtained from dispersion relation given by equation (3.11), is shown in Figure 3.2 and Figure 3.3 respectively.

Figure 3.2: Variation of normalized wave vector \([K(\omega), L]\) versus normalized frequency showing the dispersion relation for PPC1.

Figure 3.3: Variation of normalized wave vector \([K(\omega), L]\) versus normalized frequency showing the dispersion relation for PPC2.

For PPC1, if we take the thickness ratio \( d \) to be equal to 0.01, we get only one photonic band gap that lies in the normalized frequency range from 1.322 to 1.358 centered at 1.340 with a forbidden band width of 0.036. On the other hand, for \( d=0.10 \) (10 times the width of plasma layer of the
previous case), the forbidden band gap lies in the normalized frequency range 1.240 to 1.482 centered at 1.360 with a band width of 0.242. It is clear that if we increase the thickness of plasma layer by 10 times, the forbidden band width increases by 7 times approximately. Also, the mid point of the band gap shifts slightly towards the higher values of the normalized frequency when the thickness of the plasma layers is increased and the thickness of the dielectric layer is decreased from the same value.

For PPC2, if we take the thickness ratio (d) to be equal to 0.01, we obtain two band gaps in the same normalized frequency range as for PPC1. The first band gap lies in the normalized frequency range from 1.291 to 1.316 centered at 1.303 with a band width of 0.025. The second band gap lies between 1.507 and 1.531 of normalized frequency centered at 1.520 with a band width of 0.024. For the both band gaps the band widths are almost equal. However, for d=0.10, the first band gap in PPC2 lies in the normalized frequency range from 1.209 to 1.371 centered at 1.290 with a band width of 0.162 and the second band gap lies from 1.415 to 1.578 centered at 1.497 with a band-width of 0.163. Thus, if we increase the width of plasma layers by 10 fold, the widths of the forbidden band gaps increase by 6.5 times on an average. But unlike the case of PPC1, in this case, the mid points of the band-gaps shift towards the lower end of the normalized frequency. It is clear from the Figure 3.2 and Figure 3.3 that if we increase the thickness of the plasma layers, the width of photonic band gap also increases same as what Hojo and Mase [7] and also Ojha et al [8] reported earlier. Comparing the two structures of one dimensional plasma photonic crystals PPC1 and PPC2, the widths of allowed and forbidden bands of PPC with low refractive index dielectric material are more than the corresponding bands of PPC with high refractive index dielectric material.
Figure 3.4 and Figure 3.5 show the variation of the reflectivity (obtained from equation (3.16) as a function of normalized frequency parameter for the two structures discussed here, namely, PPC1 and PPC2 respectively. It is quite clear from the study of the graphs that for $d=0.01$, the reflectivity of both PPCs is not very large in the entire range of the normalized frequency but it is appreciable for the regions where there is a forbidden band.

Figure 3.4: Variation of reflectance versus normalized frequency for PPC1.

Figure 3.5: Variation of reflectance versus normalized frequency for PPC2.
In PPC1, the region with substantial reflectivity occurs in very narrow ranges i.e. 1.322 to 1.358 of the normalized frequency parameter centered at 1.340; and in PPC2, it occurs in two regions i.e. from 1.291 to 1.316 centered at 1.303 and 1.507 to 1.531 centered at 1.520.

If we increase the width of the plasma layers by 10 times, we get 100% reflectivity for both PPCs over certain ranges of normalized frequency parameter. For PPC1, the 100% reflectivity occurs from 1.240 to 1.482 of the normalized frequency parameter centered at 1.360; and for PPC2 the 100% reflectivity occurs in regions from 1.209 to 1.371 and from 1.415 to 1.578 of the normalized frequency parameter centered at 1.290 and 1.497 respectively.

Thus, in the case of PPC1, as the width of plasma layers is increased, the centre of high reflectivity ranges shifts towards the higher normalized frequency side; and for PPC2, the centre of high reflectivity ranges shifts towards the lower normalized frequency side as one increases the thickness of the plasma layers. Hence, by adjusting the thickness of plasma layers and choosing proper material for dielectric layers, we can shift the centre of high reflectivity towards lower or higher frequency range.

Plots of equation (3.13) with respect to normalized frequency gives an idea how the effective group velocity \((V_g)\) in the two structures changes as we change various parameters of the PPC structures. The resulting graphs shown in Figure 3.6 and Figure 3.7 corresponding to PPC1 and PPC2 respectively show that the group velocity in each of the PPC structures becomes negative in certain range(s) of normalized frequency; and it tends to zero at the band edges. Thus, negative group velocity \((V_g<0)\) is an anomalous behaviour of PPCs.
For PPC 1, if we take $d=0.01$, the group velocity ($V_g$) is negative only in the first allowed band i.e. 1.038 to 1.322 (the width of the range of frequency being 0.292) of the normalized frequency. But the group velocity ($V_g$) is positive corresponding to second allowed band i.e. 1.358 to 1.650 (width being 0.292) of the normalized frequency.

Figure 3.6: Variation of group velocity versus normalized frequency for PPC1.

Figure 3.7: Variation of group velocity versus normalized frequency for PPC2.

If we take $d=0.10$, the range in first allowed band over which the group velocity ($V_g$) is negative reduces to a great extent i.e. from 1.180 to 1.240 (width being 0.060); and the group velocity ($V_g$) is found to be positive in the second allowed band i.e. 1.482 to 1.552 (width being 0.070).
If we take similar value of thickness of the plasma layers in the case of PPC2, the group velocity is found to be negative corresponding to first and third allowed bands and positive corresponding to second allowed band. If we choose \( d = 0.01 \), the group velocity has negative value corresponding to first allowed band from \( 1.100 \) to \( 1.291 \) of the normalized frequency (width being \( 0.191 \)) and also corresponding to third allowed band from \( 1.531 \) to \( 1.722 \) (width being \( 0.191 \)) of the normalized frequency. However, the group velocity is positive corresponding to second allowed band from \( 1.316 \) to \( 1.507 \) of the normalized frequency. If we choose \( d = 0.10 \) the group velocity has negative values corresponding to first allowed band from \( 1.176 \) to \( 1.209 \) (with total width of \( 0.043 \)) and the third allowed band \( 1.578 \) to \( 1.630 \) (with total width of \( 0.045 \)). However, the group velocity has positive values corresponding to second allowed band from \( 1.371 \) to \( 1.415 \) (with total width of \( 0.045 \)). Thus, for PPC1, we can obtain one region of negative group velocity and one region of positive group velocity but for PPC2, we can obtain two regions of negative group velocity and one region of positive group velocity for the same range of normalized frequency. For both the PPC structures with different \( d \) values, the group velocity tends to zero at the band edges. The magnitude of group velocity for a particular value of normalized frequency is larger for \( d = 0.01 \) than that of \( d = 0.10 \) in each of the structures.

Thus, if we decrease the thickness of plasma layers of PPCs, the magnitude of group velocity increases. Thus, the plasma width is the controlling parameter of group velocity. The negative group velocity \((V_g < 0)\) of electromagnetic waves in PPCs is an abnormal behaviour and it is responsible for superluminal behaviour in PPCs. From Figure 3.6, it is clear that there are left-right and up-down symmetries and it supports two
different states. These states of symmetry may be used to make devices involving flip-flops like logic gates, optical switches (for optical computing) etc. PPC1 has two different states of flip-flop for a large normalized frequency range (1.0-1.7), whereas PPC2 works as a flip-flop for a short normalized frequency range (1.05-1.51).

The effective group index $n_{\text{eff}}(g)$ is computed from equation (3.14) and the corresponding graphs shown in Figures 3.8 and 3.9. It is found that the effective group index becomes negative within PPCs in certain regions of the normalized frequency parameter because of the abnormal behaviour of group velocity. For both PPCs, if we decrease the thickness of plasma layers, there is an increase in both the ultra low and ultra high values of effective group index.

![Figure 3.8: Variation of effective group index of refraction versus normalized frequency for PPC1.](image)

For PPC1, the ultra low and ultra high values of $n_{\text{eff}}(g)$ is large. But for PPC2, these values are lesser than the corresponding values of PPC1. The group velocity as well as $n_{\text{eff}}(g)$ becomes negative corresponding to the allowed bands for which the value of wave vector $K(\omega)$ decreases as the normalized frequency increases. On the other hand, the group velocity as
well as \( n_{\text{eff}}(g) \) becomes positive corresponding to the allowed band for which the value wave vector \( K_{(0)} \) increases as normalized frequency increases.

![Figure 3.9: Variation of effective group index of refraction versus normalized frequency for PPC2.](image)

**3.3.2 Case II:** \( \gamma > \gamma_p \)

For this case, band structure, reflectivity, group velocity and effective group index are obtained from Equations (3.12), (3.13), (3.14) and (3.16) respectively. Figures 3.10 and 3.11, shows the dispersion relations (variation of normalized wave vector vs normalized frequency) for PPC1 and PPC2 respectively.

![Figure 3.10: Variation of normalized wave vector \([K(\omega).L]\) versus normalized frequency showing the dispersion relation for PPC1.](image)
The corresponding band gaps for both PPCs are shown in Table 3.1. From Table 3.1 it is clear that if we increase the value of \( d \), the forbidden band gaps also increase. For PPC1 the band width of \( d = 0.10 \) is 6 times larger than that of \( d = 0.01 \) and for PPC2 the band width of \( d = 0.10 \) is 5 times approximately than that of \( d = 0.01 \). But in case 1 it was approximately 7 times larger.

<table>
<thead>
<tr>
<th>Value of ( d )</th>
<th>PPC1</th>
<th>PPC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d = 0.01 )</td>
<td>Band Gap ((\omega L/2\pi c))</td>
<td>Band width</td>
</tr>
<tr>
<td>1.320-1.330</td>
<td>0.010</td>
<td>1.290-1.305</td>
</tr>
<tr>
<td>1.650-1.660</td>
<td>0.010</td>
<td>1.507-1.524</td>
</tr>
<tr>
<td>1.715-1.735</td>
<td>0.020</td>
<td></td>
</tr>
<tr>
<td>( d = 0.10 )</td>
<td>Band Gap ((\omega L/2\pi c))</td>
<td>Band width</td>
</tr>
<tr>
<td>1.220-1.280</td>
<td>0.060</td>
<td>1.205-1.280</td>
</tr>
<tr>
<td>1.540-1.600</td>
<td>0.060</td>
<td>1.408-1.492</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.625-1.719</td>
</tr>
</tbody>
</table>

Here, if we increase the value of \( d \), the band gap also shifts towards the lower normalized frequency region. Also, the mid points of band gaps are not in same region.
The reflectivity curves are shown in Figures 3.12 and 3.13 for PPC1 and PPC2 respectively. The 100% reflection ranges corresponding to the band gaps shifts towards the lower normalized frequency region as we increase the value of d.

Figure 3.12: Variation of reflectance versus normalized frequency for PPC1.

Figure 3.13: Variation of reflectance versus normalized frequency for PPC2.
The group velocities and effective group index are shown in Figures 3.14, 3.15 and Figures 3.16 and 3.17 respectively.

Figure 3.14: Variation of group velocity versus normalized frequency for PPC1.

Figure 3.15: Variation of group velocity versus normalized frequency for PPC2.

From Figures 3.14 and 3.15 it is clear that the group velocities are positive and negative for the certain ranges of frequencies. The positive and negative values are not in perfect symmetrical fashion for d=0.01. But if we increase the value of d, the structures attains best symmetrical results.
Figure 3.16: Variation of effective group index of refraction versus normalized frequency for PPC1.

Figure 3.17: Variation of effective group index of refraction versus normalized frequency for PPC2.

From the Figures 3.16 and 3.17, it is clear that the values of effective group index for \( d = 0.01 \) have high positive than that of \( d = 0.10 \) for both PPCs. But the magnitude of negative values of group velocity for \( d = 0.10 \) have high values. In this way we can choose the appropriate value of \( d \) for achieving high magnitude of positive and negative values of group velocity. Thus, PPCs may be used as a flip flop because of their up-down symmetries.
3.4 Conclusion

This study shows that the thickness of plasma layers in PPCs control the forbidden band gaps. So we can use a PPC as a broadband reflector and frequency selector by choosing appropriate values of plasma thickness and suitable material for dielectric layers. For PPC1, the mid point of a band gap shifts towards the higher normalized frequency range, whereas for PPC2 the mid point of a band gap shifts towards the lower normalized frequency range by increasing the thickness of the plasma layers. For certain normalized frequency range, the group velocity becomes negative. Because of this abnormal behaviour \( (V_g < 0) \), superluminal flow of photon occurs in the PPCs. Such structures may be considered as a flip-flop as there is positive and negative symmetry of effective group velocity. From the above discussion, it is clear that the PPCs can be used as a flip-flop for both cases \(( < \bar{\omega}_p \text{ and } > \bar{\omega}_p \)). But it gives better results for case I because in this case, we get a perfect symmetry and the band gap lies in the same region as we increase the value of \( d \). Also, the broadening of forbidden band gaps with the increase of \( d \) is more for Case I. This symmetry is exhibited by PPC1 for a wide normalized frequency range, and hence such a structure may considered for the design of a flip flop working over a wide range of frequency. On the other hand, the structure PPC2 may be considered for the design of a flip flop working over narrower range of normalized frequency. Since PPC2 has two critical values of normalized frequency where change of states takes place, it may be used in the design of composite flip-flops. It also exhibits superluminal propagation both for the smaller and larger values of normalized frequency. Such a flip-flop, in principle, may be used to making logic gates, optical switches in optical computing.
References:


