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ENHANCEMENT OF OMNIDIRECTIONAL REFLECTION BANDS IN ONE-DIMENSIONAL PHOTONIC CRYSTALS WITH LEFT-HANDED MATERIALS

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Abstract—In this paper we show, theoretically, that total omnidirectional reflected frequency band is enlarged considerably by using one-dimensional photonic crystal (PC) structure composed of alternate layers of ordinary material (OM) and left handed material (LHM). From the analysis it is found that the proposed structure has very wide range of omnidirectional total frequency bands for both polarizations in comparison to the normal PC structure, which consists of alternate layers of ordinary material having positive index of refraction. The proposed structure also has an absolute band gap that can be exploited to trap the light.

1. INTRODUCTION

Over a past decade Photonic Crystals (PCs) have received a considerable attention for their use in fundamental physics studies as well as for potential applications in photonic devices [1–4]. The PCs are composite structure of materials with different dielectric constants on the length scale comparable to optical wavelength. The main features of the PCs are that they can prohibit the propagation of electromagnetic waves within a certain frequency range called Photonic Band Gap (PBG). These composite structures affect the properties of photons in much the same way as semiconductor affects the properties of electrons.

The high reflectivity of one-dimensional PC usually called Bragg mirror or Bragg reflector is a well-known phenomenon that has been studied for a long time. Reflectors are one of the most widely used optical devices, which are mainly of two types: one of them is the metallic reflector and other one is a multilayer dielectric reflector. In metallic reflector light can be reflected over a wide range of frequencies for arbitrary incident angles. However, at higher frequencies there is considerable power loss due to the absorption. In comparison to metallic reflectors a multilayer dielectric reflectors have high reflectivity in a certain range of frequencies, but the reflectivity is very sensitive to the incident angles.

Recently many authors have shown that the total reflection frequency range of a multilayer dielectric reflector can be enhanced by the proper selection of the refractive index and thickness of the layers and also by using the photonic hetero structures [5–10].

In the present communication we show, theoretically, that total omnidirectional reflection bands can be enlarged by using one-dimensional PCs containing left-handed materials (LHMs). The left-handed materials (LHMs) also called negative index materials (NIMs) or double negative (DNG) materials are artificial composite with both negative permittivity ε and permeability μ. These materials have attracted a great deal of interest [11–17] due to its unusual electromagnetic properties such as inverse Snell's law (negative refraction), antiparallel group and phase velocity, reverse Doppler shift and reverse Cerenkov radiation. When an electromagnetic plane wave propagates through these types of material, the direction of Poynting vector $\mathbf{S} = \mathbf{E} \times \mathbf{H}$ will be opposite to that of wave vector so that $\mathbf{k}, \mathbf{E}$ and $\mathbf{H}$ form a left-handed set of vectors. Thus when such type of material is used in PC a very distinct feature is observed. In order to implement our idea we consider 1D PC consisting of alternate layers of positive index material (PIM) and negative index material (NIM). The proposed structure is capable to reflect a large portion of EM wave for both polarizations (TE and TM) and for all the incident angles. The total reflection frequency range is compared to the normal photonic crystal structure that consists of alternate layers of dielectric materials having positive index of refraction. To show that PC structure containing periodic arrangement of PIM and NIM can enhance the band gap and omnidirectional frequency band, we compute the band structure and reflectance spectra for both types of PCs.

2. THEORETICAL DEVELOPMENT

To calculate the dispersion relation and reflection characteristics for the incident electromagnetic wave, the Maxwell's equation is solved numerically by the transfer matrix method [18].

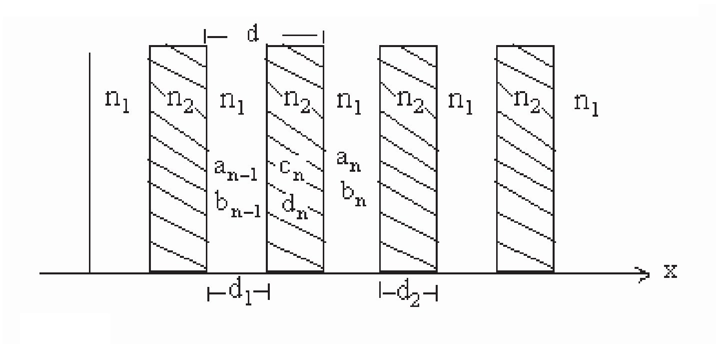

Figure 1. The periodic refractive index profile of the structure have refractive indices n_1 and n_2 respectively.

The geometry of the structure under study is shown in the Fig. 1. Consider the propagation of EM wave along x-axis normal to the interface in one-dimensional system composed of periodic arrays of two different materials with a refractive index n_1 and n_2 and layer thickness d_1 and d_2. The refractive index profile of the structure is

$$n(x) = \begin{cases} n_1, 0 < x < d_1 \\ n_2, d_1 < x < d \end{cases} \tag{1}$$

with $n(x) = n(x + d)$. Here, $d = d_1 + d_2$ is the period of the lattice (or lattice constant). To solve for the electric field vectors of the Bloch wave, we use Transfer Matrix Method as described in Ref. [18]. The electromagnetic field distribution within each layer can be expressed as the sum of right- and left-hand side propagating wave. The electric field within the both layers of the nth unit cell can be written as

$$E_1(x) = \left[\left(a_n e^{-ik_1(x-nd)}\right) + b_n e^{ik_1(x-nd)}\right] e^{i\omega t} \tag{2a}$$

$$E_2(x) = \left[\left(c_n e^{-ik_2(x-nd)}\right) + b_n e^{ik_2(x-nd)}\right] e^{i\omega t} \tag{2b}$$

where $k_i = \left[\left(\frac{n_i\omega}{c}\right)^2 - \beta^2\right]^{1/2} = \frac{n_i\omega}{c}\cos\theta$; θ_i is the ray angle in the ith layer $(i = 1, 2)$, β is the propagation constant and $n_i = \sqrt{\varepsilon_i\mu_i}$, where ε_i and μ_i are the dielectric permittivity and magnetic permeability of the constituent layers.

The coefficients a_n, b_n, c_n, and d_n are related through the continuity conditions at the interfaces $x = (n-1)d$ and $x = (n-1)d + d_2$. This continuity condition leads to the matrix equations, which relates the coefficient in the first layer of the nth cell, is given as

$$\begin{bmatrix} a_{n-1} \\ b_{n-1} \end{bmatrix} = T_n \begin{bmatrix} a_n \\ b_n \end{bmatrix} \tag{3}$$

where T_n is called the transfer matrix given by

$$T_n = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{4}$$

The matrix elements A, B, C and D are

$$A = e^{ik_1 d_1}\left[\cos k_2 d_2 + \frac{1}{2} i \left(\eta + \frac{1}{\eta}\right) \sin k_2 d_2\right]; \tag{5a}$$

$$B = e^{-ik_1 d_1}\left[\frac{1}{2} i \left(\eta - \frac{1}{\eta}\right) \sin k_2 d_2\right] \tag{5b}$$

$$C = e^{-ik_1 d_1}\left[-\frac{1}{2} i \left(\eta - \frac{1}{\eta}\right) \sin k_2 d_2\right]; \tag{5c}$$

$$D = e^{-ik_1 d_1}\left[\cos k_2 b - \frac{1}{2} i \left(\eta + \frac{1}{\eta}\right) \sin k_2 d_2\right]; \tag{5d}$$

The parameter η depends on the polarization. For the TE and TM polarizations, η is given by

$$\eta_{TE} = \frac{k_1}{k_2} \qquad \text{and} \qquad \eta_{TM} = \frac{k_1 n_2^2}{k_2 n_1^2}$$

For finite stacks, the coefficient of right and left hand side propagating wave in both sides of the multiplayer structure a_N and b_N, are calculated by multiplying transfer matrix of each cell as

$$\begin{bmatrix} a_0 \\ b_0 \end{bmatrix} = T_1 T_2 \ldots\ldots T_N \begin{bmatrix} a_N \\ b_N \end{bmatrix}, \tag{6}$$

where N is the total number of the cell. The coefficient of reflection is given by solving above matrix equation with the condition $b_N = 0$ as

$$r_N = \left(\frac{b_0}{a_0}\right). \tag{7}$$

Thus the reflectivity (or reflectance) of the structure may be calculated as

$$R_N = |r_N|^2. \tag{8}$$

Now, according to Bloch theorem, the electric field vector is of the form $E = E_k(x)e^{i(\omega t - Kx)}$, where $E_K(x)$ is periodic with the period 'd'. For the determination of K as a function of eigen value, the equation is written as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} a_n \\ b_n \end{bmatrix} = e^{iKd} \begin{bmatrix} a_n \\ b_n \end{bmatrix} \tag{9}$$

The solution of this matrix equation leads to the dispersion relation for the PC structure containing the alternate stacks of positive index materials, denoted by PC1, is given by

$$K(\omega)=\left(\frac{1}{d}\right)\cos^{-1}\left[\cos(k_1 d_1)\cos(k_2 d_2)-\frac{1}{2}\left(\eta+\frac{1}{\eta}\right)\sin(k_1 d_1)\sin(k_2 d_2)\right] \tag{10}$$

The dispersion relation for the PC structure containing the alternate layer of positive and negative index material i.e., ordinary material (OM) and left-handed materials (LHMs), denoted by PC2, is given by [16]

$$K(\omega)=\left(\frac{1}{d}\right)\cos^{-1}\left[\cos(k_1 d_1)\cos(k_2 d_2)+\frac{1}{2}\left(\eta+\frac{1}{\eta}\right)\sin(k_1 d_1)\sin(k_2 d_2)\right] \tag{11}$$

which is different from the normal PC structure, since for LHMs, $k_2 < 0$ (because $n_2 < 0$). Now we discuss theoretically the enhancement of reflection bands for PC2 structure. It has been shown in ref. [18] that the structure containing alternate layers of PIMs i.e., PC1, the imaginary parts of (Kd) at the center of the forbidden band is given by

$$(K(\omega)d)_{\max} = 2\frac{|n_2 - n_1|}{(n_2 + n_1)} \tag{12}$$

Using the same approach as used in ref. [18] the imaginary parts of (Kd) at the center of the forbidden band for the PC structure containing alternate layers of PIM and NIM i.e., PC2, is found to be

$$(Kd)_{\max} = 2\frac{(n_2 + n_1)}{|n_2 - n_1|} \tag{13}$$

Now from Eqs. (12) and (13) it is observed that the forbidden band for PC2 is much larger than that of PC1. Hence, the reflection bands

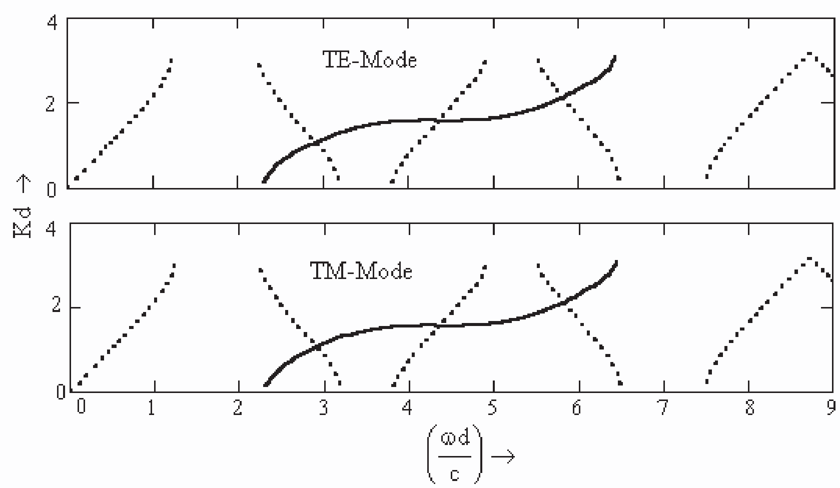

Figure 2a. The plot of dispersion relation for PC1 ($n_1 = 1.35$ and $n_2 = 3.6$) PC2 ($n_1 = 1.35$ and $n_2 = -3.6$) structure with layer thickness $d_1 = 0.8d$ and $d_2 = 0.2d$ respectively for both TE and TM modes. Dotted line is used for PC1 and solid line is used for PC2.

for PC2 are enhanced much more than PC1 for the same value of refractive index contrast. The enhancement of reflection bands can also be understood by considering Eq. (12) only. If we replace n_2 by $(-n_2)$ in Eq. (12) then $|n_2 - n_1|$ becomes $|-n_2 - n_1|$ and $(n_1 + n_2)$ becomes $(n_1 - n_2)$. Hence the value of imaginary part of Kd for PC2 takes the value $2\frac{|-n_2-n_1|}{(n_1-n_2)}$ which is larger than the value for PC1 structure. Thus the reflection bands for PC2 widened more than the PC1 for the same value of refractive index contrast.

Now in the next section we will numerically show the enhancement of the forbidden bands for PC2 in comparison to PC1.

3. RESULTS AND DISCUSSIONS

For the numerical computations, we consider two types of Photonic Crystal (PC) structures PC1 and PC2 as already mentioned. Further, if the difference between the absolute value of index increases the width of the reflection bands increases too for PC2, which is obvious from equation (12). Moreover, we have taken here the non-dispersive material for our analytical study only which is in accordance with Shadrivov et al. [21]. The refractive indices and thicknesses of the

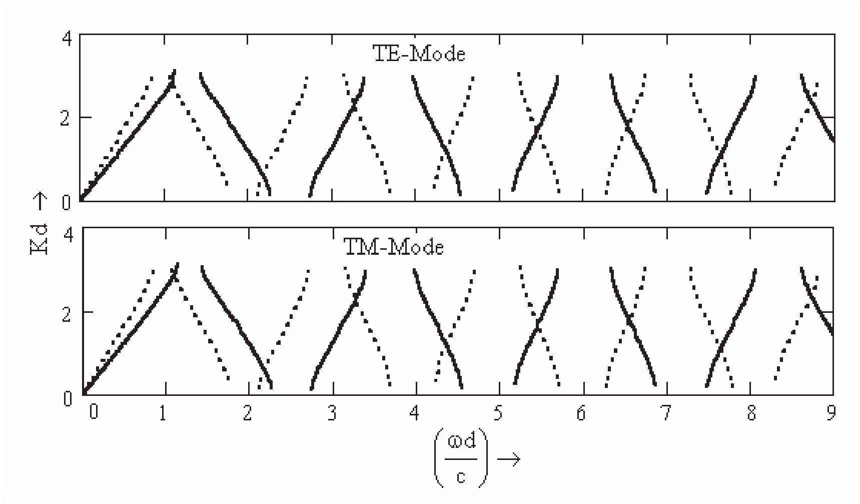

Figure 2b. The plot of dispersion relation for PC1 ($n_1 = 1.35$ and $n_2 = 3.6$) PC2 ($n_1 = 1.35$ and $n_2 = -3.6$) structure with layer thickness $d_1 = 0.2d$ and $d_2 = 0.8d$ respectively for both TE and TM modes. Dotted line is used for PC1 and solid line is used for PC2.

layers for PC1 are chosen as $n_1 = 1.35$, $n_2 = 3.6$ and $d_1 = 0.8d$, $d_2 = 0.2d$, while for the PC2 the refractive indices are $n_1 = 1.35$, $-n_2 = 3.6$ and the layer thicknesses are the same as in the case of PC1.Here, we take $\mu_1 = -\mu_2 = 1$ for comparison with PC1 in which permeability is set to be 1.0 [19–20]. Photonic band structure obtained from Eqs. (10)–(11) in terms of normalized frequency for the normal incident is shown in the Figs. 2(a)–2(b). It can be seen from the Fig. 2(a) that the width of the forbidden bands for PC2 is much larger than those of PC1, though the nature of curve is different. But when the thicknesses of the layers are reversed i.e., if d_1 and d_2 are taken as $0.2d$ and $0.8d$, then both PCs have the same nature of curve. In general for $d_1 < d_2$ the nature of curve for PC2 is similar to that of PC1. In this case also the width of the forbidden (reflection) bands for PC2 is larger than those of PC1. At the same time the band shifts towards the higher frequency region for PC2. For PC1 there are four band gaps, which ranges about 1.24 to 2.22 ($\omega d/c$), 3.22 to 3.83 ($\omega d/c$), 4.90 to 5.50 ($\omega d/c$) and 6.50 to 7.50 ($\omega d/c$) whereas PC2 has only two band gaps raging from 0.2 to 2.26 ($\omega d/c$) and 6.42 to 8.52 ($\omega d/c$) for the normal incidence. Thus PC2 has much wider band gaps than PC1 for all frequencies. Here, we have shown the band structures for both TE and TM polarizations. In this way PC structure containing OM-LHM combination enhances the band gaps.

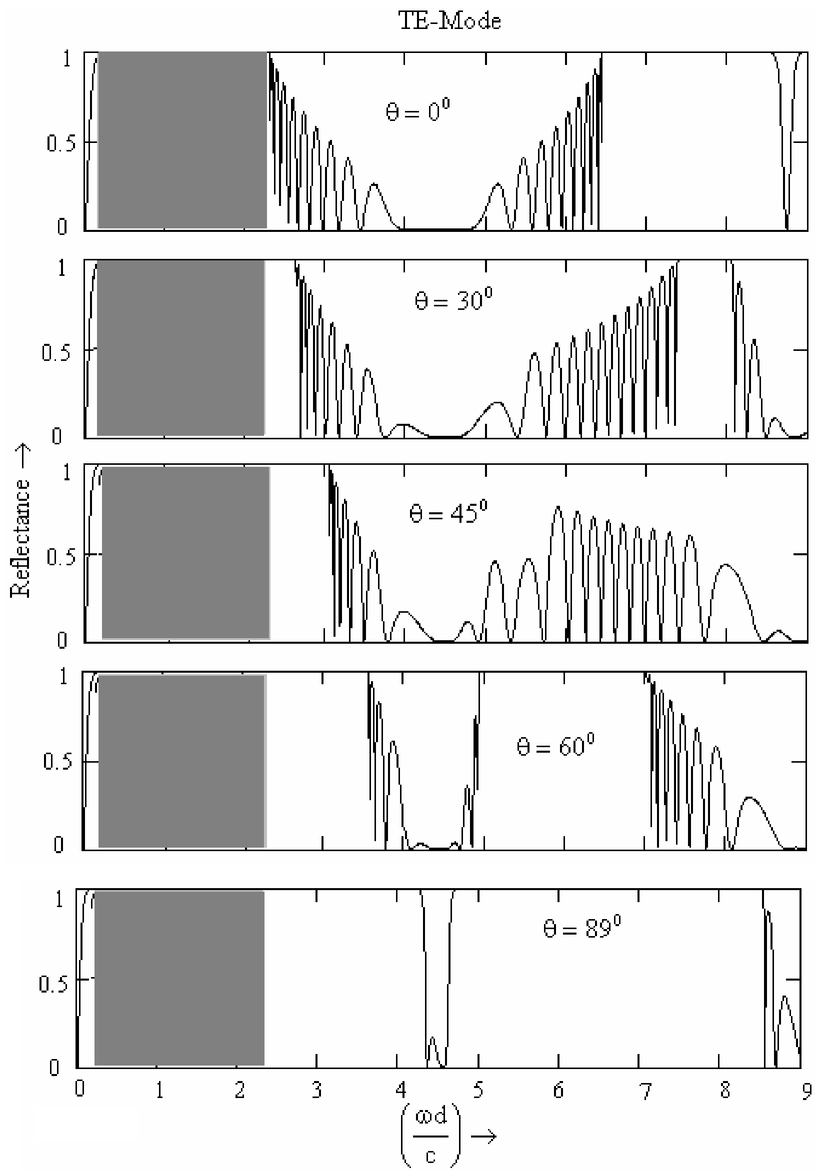

Figure 3a. Reflectance curve for PC2 structure having $n_1 = 1.35$ and $n_2 = -3.6$ and layer thickness $d_1 = 0.8d$ and $d_2 = 0.2d$ respectively for both TE and TM polarizations respectively.

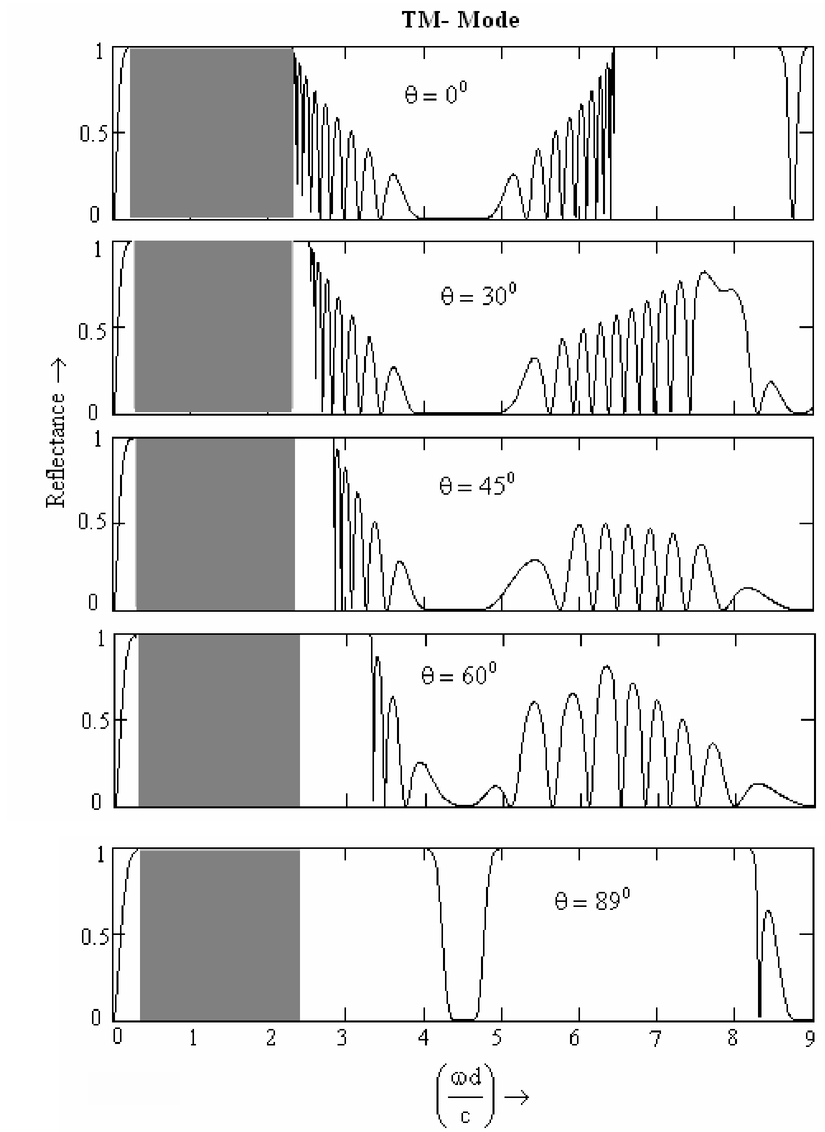

Figure 3b. Reflectance curve for PC2 structure having $n_1 = 1.35$ and $n_2 = -3.6$ and layer thickness $d_1 = 0.8d$ and $d_2 = 0.2d$ respectively for both TE and TM polarizations respectively.

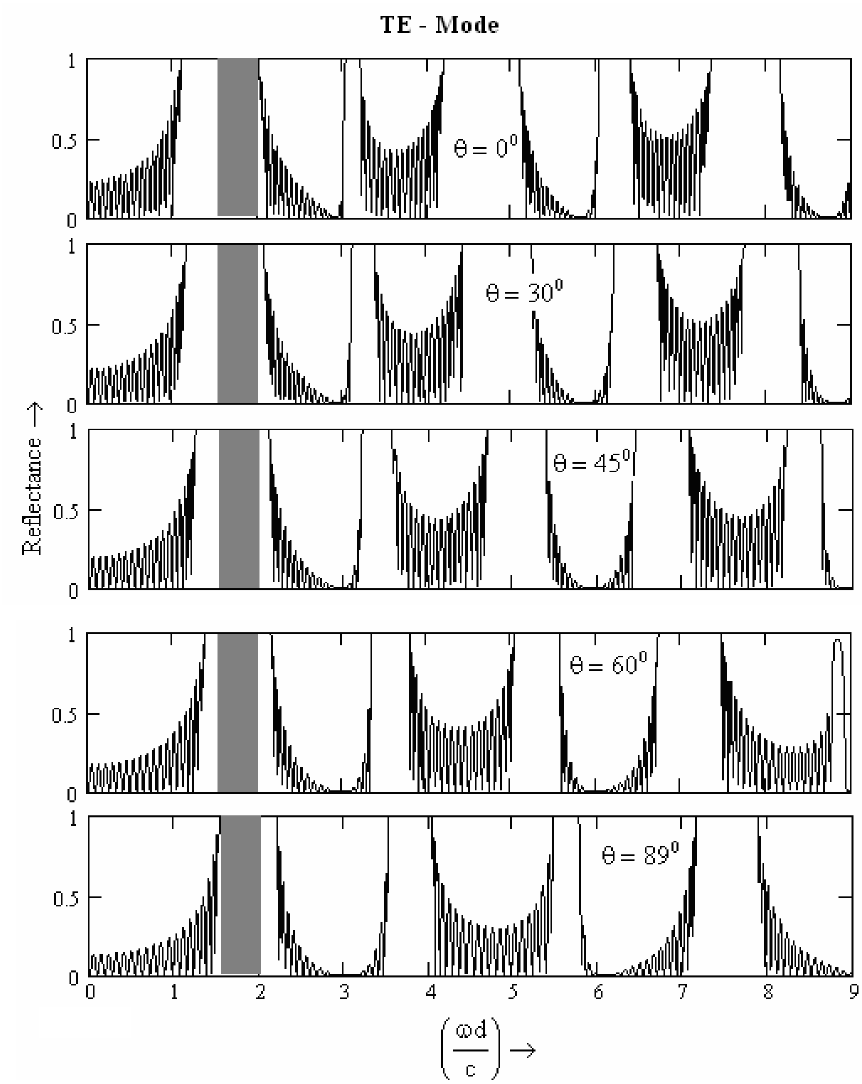

Figure 4a. Reflectance curve for PC1 structure having $n_1 = 1.35$ and $n_2 = 3.6$ and layer thickness $d_1 = 0.8d$ and $d_2 = 0.2d$ respectively for both TE and TM polarizations respectively.

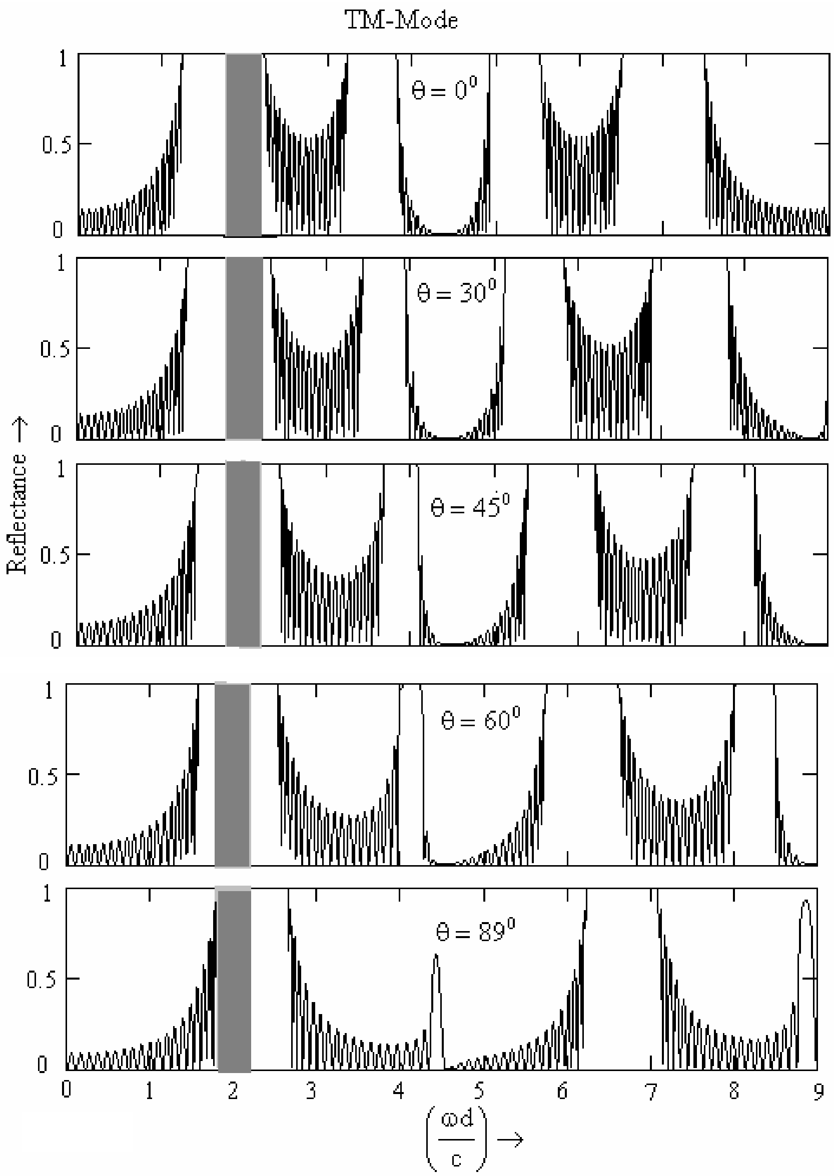

Figure 4b. Reflectance curve for PC1 structure having $n_1 = 1.35$ and $n_2 = 3.6$ and layer thickness $d_1 = 0.8d$ and $d_2 = 0.2d$ respectively for both TE and TM polarizations respectively.

Table 1. Total reflected frequency range for PC2 having $d_1 = 0.8d$ and $d_2 = 0.2d$.

Incident Angle	Band Gap (in normalized frequency($\omega d/c$))	
	TE-Polarization	TM-Polarization
$\theta = 0^0$	0.20 – 2.26 6.42 – 8.52	0.20 – 2.26 6.42 – 8.52
$\theta = 30^0$	0.19 – 2.65 7.35 – 7.95	0.21 – 2.52 ------------
$\theta = 45^0$	0.17 – 3.03	0.23 – 2.84
$\theta = 60^0$	0.14- 3.58 4.95 – 7.0	0.25 – 3.3 ------------
$\theta = 89^0$	0.12 – 4.25 4.65 – 8.52	0.37 – 4.0 4.98 – 8.0

Table 2. Total reflected frequency range for PC1 having $d_1 = 0.8d$ and $d_2 = 0.2d$.

Incident Angle	Band Gap (in normalized frequency ($\omega d/c$))	
	TE-Polarization	TM-Polarization
$\theta = 0^0$	1.24 – 2.22 3.22 – 3.83 4.90 – 5.50 6.50 – 7.50	1.24 – 2.22 3.22 – 3.83 4.90 – 5.50 6.50 – 7.50
$\theta = 30^0$	1.28 – 2.35 3.38 –3.98 5.05 – 5.98 6.85 – 7.85	1.35 – 2.30 3.45 – 3.92 5.13 – 5.80 6.92 – 7.78
$\theta = 45^0$	1.30 –2.53 3.62 – 4.18 5.25 – 6.30 7.30 – 8.21	1.44 – 2.42 3.68 – 4.08 5.40 – 6.20 7.40 – 8.10
$\theta = 60^0$	1.31 – 2.80 3.93 – 4.31 5.48 – 6.84 7.87 – 8.60	1.58 – 2.55 4.0 – 4.21 5.76 – 6.60 8.0 – 8.48
$\theta = 89^0$	1.35 – 3.10 5.73 – 7.50	1.80 – 2.64 6.25 – 7.06

Table 3. Total reflected frequency range for PC2 having $d_1 = 0.7d$ and $d_2 = 0.3d$.

Incident Angle	Band Gap (in normalized frequency($\omega d/c$))	
	TE-Polarization	TM-Polarization
$\theta = 0^0$	0.11–2.70 3.65–5.35	0.11–2.70 3.65–5.35
$\theta = 30^0$	0.11–2.67 4.20–5.09	0.13–2.61 ....
$\theta = 45^0$	0.12–2.63	0.15–2.45
$\theta = 60^0$	0.10–2.60 6.56–8.43	0.19–2.15 ....
$\theta = 89^0$	0.10–2.57 6.28–8.93	0.31–1.42 6.65–8.66

To show that photonic crystal structure with alternate layers OM-LHM, can enlarge the omnidirectional total reflection frequency range, reflectance spectra of the PC2 for both TE and TM polarizations at different incident angles are shown in the Figs. 3(a)–3(b) for which the total number of layers are taken as $N = 20$. These reflectance spectra are compared with that of PC1 for the same lattice parameters, which are depicted in the Figs. 4(a)–4(b). From this study, it is found that for normal incidence, the TE and TM polarizations are degenerate. There are four total frequency ranges for PC1 which are 1.24 to 2.22 ($\omega d/c$), 3.22 to 3.83 ($\omega d/c$), 4.90 to 5.50 ($\omega d/c$) and 6.50 to 7.50 ($\omega d/c$) and for PC2 there are only two total frequency ranges that lie from 0.2 to 2.26 ($\omega d/c$) and 6.42 to 8.52 ($\omega d/c$) respectively.

It is worth to be noted that the total reflected frequency bands are enlarged considerably in the case of PC2 in the low frequency range for both TE and TM mode. The total reflected frequency bands for the incident angles 30°, 45°, 60° and 89° including 0° for both PCs are shown in the Tables 1–2 respectively. From these results it is observed that PC2 has much wider reflection bands (where the reflectivity is 100%) than PC1 for all the incident angles and for both polarizations. Hence, the omnidirectional total reflection frequency bands are enlarged substantially for PC2 in TE and TM polarization, which is about 0.2 to 2.26 ($\omega d/c$) whereas it lies only in the range 1.24 to 2.22 ($\omega d/c$) for PC1. The study of reflectance spectra also

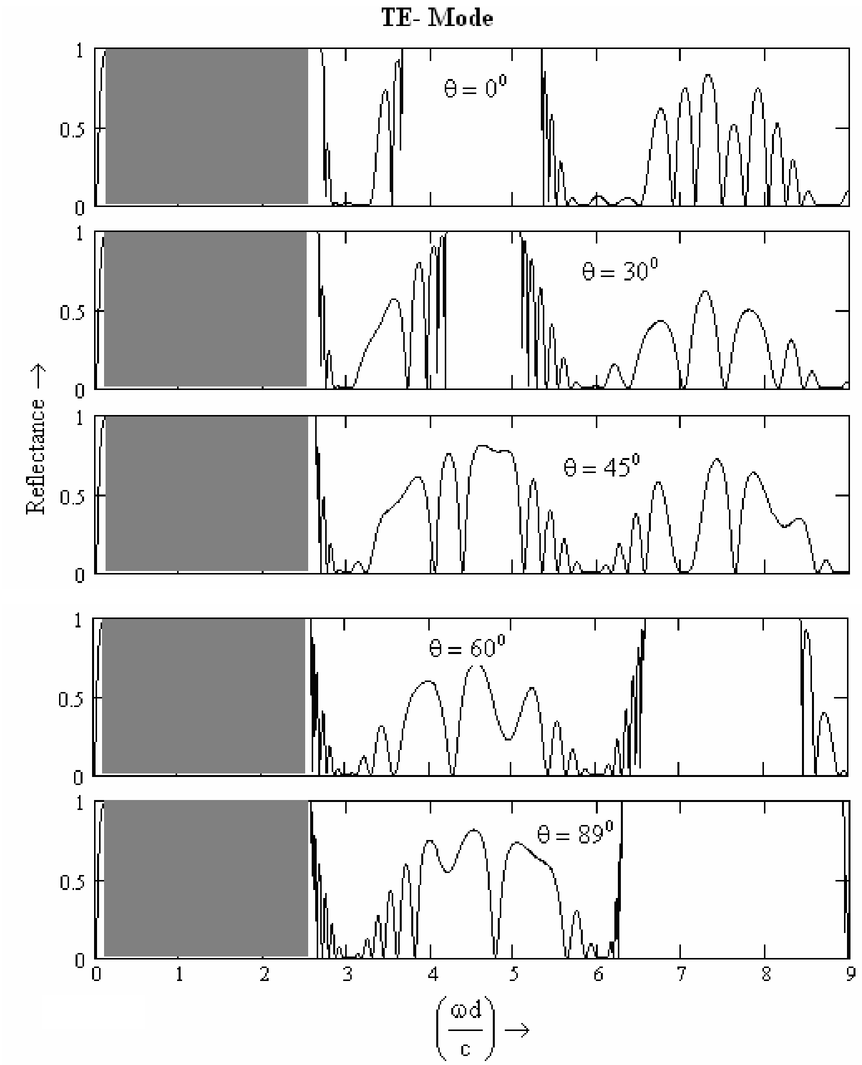

Figure 5a. Reflectance curve for PC2 structure having $n_1 = 1.35$ and $n_2 = -3.6$ and layer thickness $d_1 = 0.7d$ and $d_2 = 0.3d$ respectively for both TE and TM polarizations respectively.

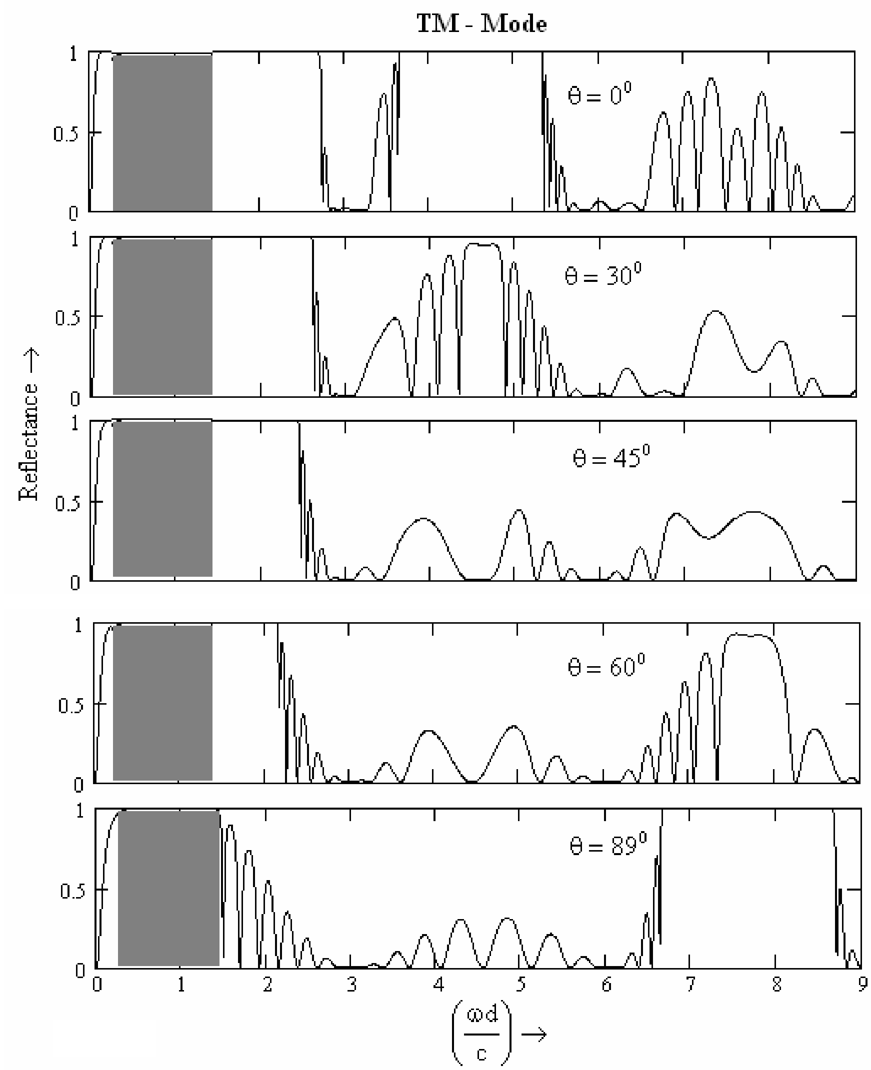

Figure 5b. Reflectance curve for PC2 structure having $n_1 = 1.35$ and $n_2 = -3.6$ and layer thickness $d_1 = 0.7d$ and $d_2 = 0.3d$ respectively for both TE and TM polarizations respectively.

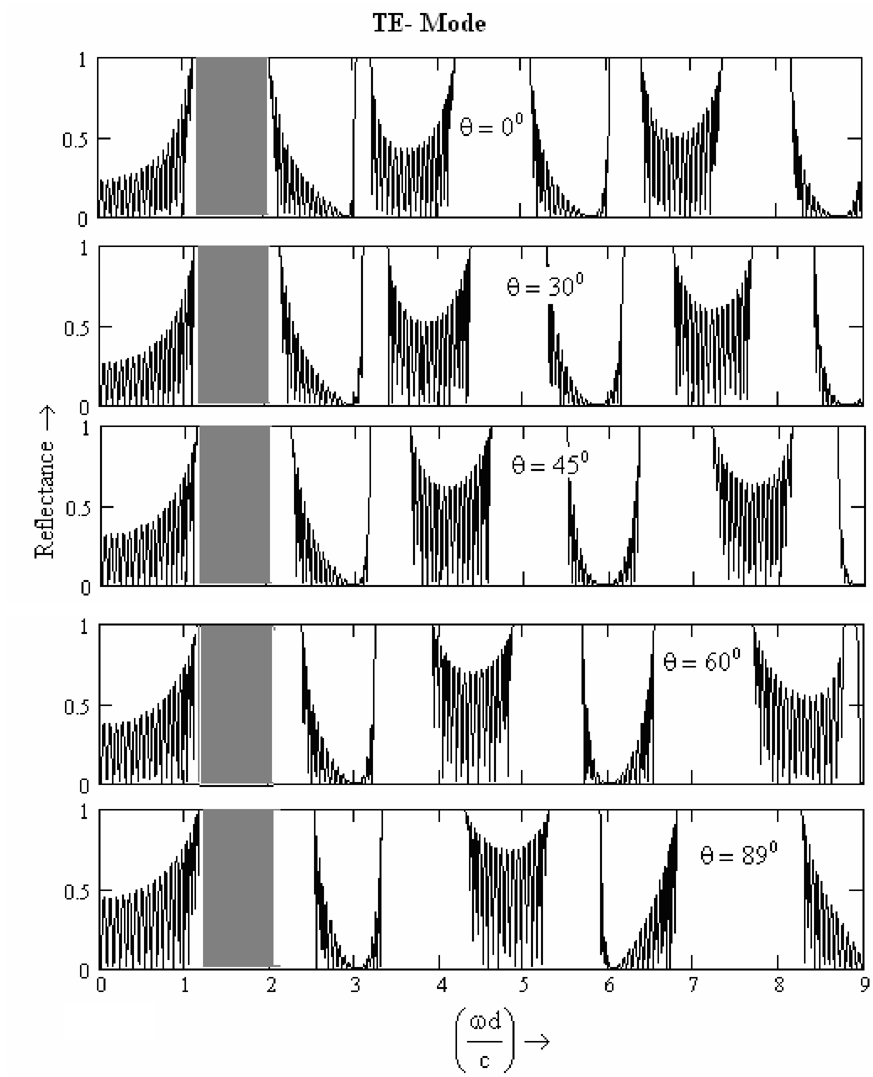

Figure 6a. Reflectance curve for PC1 structure having $n_1 = 1.35$ and $n_2 = 3.6$ and layer thickness $d_1 = 0.7d$ and $d_2 = 0.3d$ respectively for both TE and TM polarizations respectively.

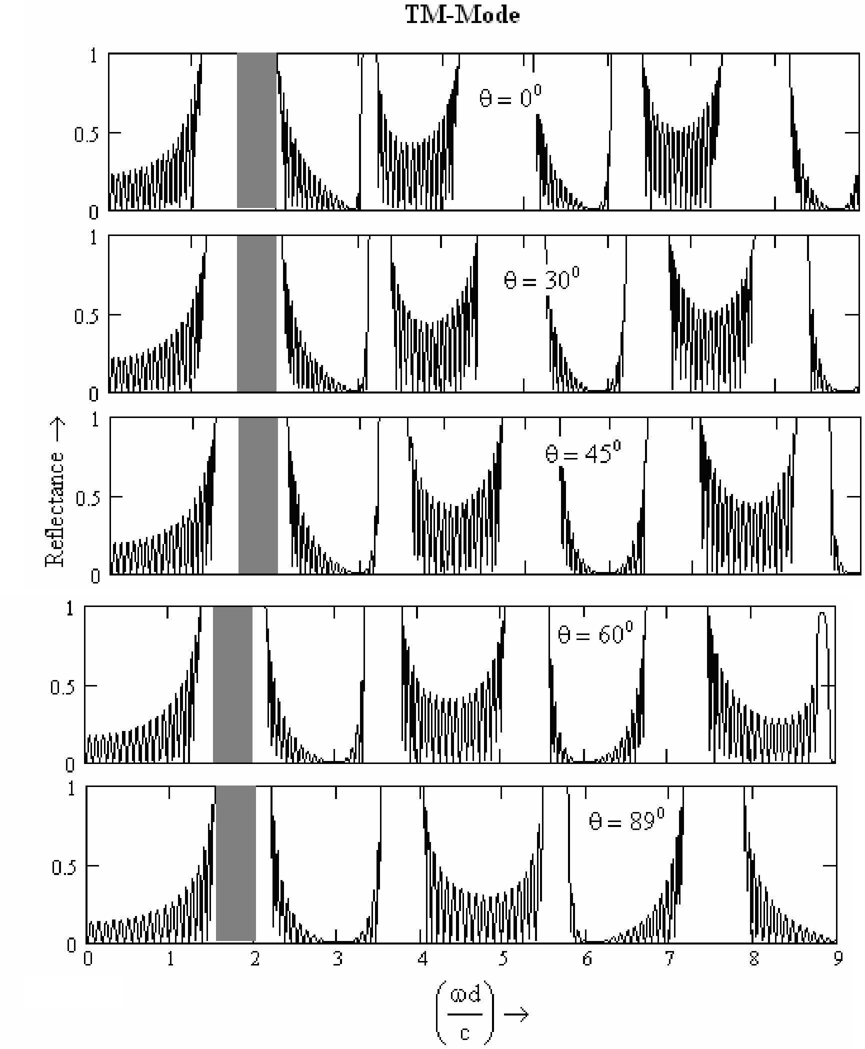

Figure 6b. Reflectance curve for PC1 structure having $n_1 = 1.35$ and $n_2 = 3.6$ and layer thickness $d_1 = 0.7d$ and $d_2 = 0.3d$ respectively for both TE and TM polarizations respectively.

Table 4. Total reflected frequency range for PC1 having $d_1 = 0.7d$ and $d_2 = 0.3d$.

Incident Angle	Band Gap (in normalized frequency $(\omega d/c)$)	
	TE-Polarization	TM-Polarization
$\theta = 0^0$	1.09—2.01 3.03—3.20 4.18—5.09 6.04—6.40 7.34—8.16	1.09—2.01 3.03—3.20 4.18—5.09 6.04—6.40 7.34—8.16
$\theta = 30^0$	1.09—2.12 3.09—3.39 4.38—5.29 6.18—6.76 7.68—8.42	1.15—2.07 3.11—3.37 4.42—5.24 6.20—6.72 7.74—8.38
$\theta = 45^0$	1.11—2.24 3.16—3.62 4.58—5.49 6.32—7.21 8.14—8.68	1.11—2.12 3.20—3.57 4.69—5.40 6.42—7.09 8.21—8.63
$\theta = 60^0$	1.12—2.39 3.23—3.92 4.86—5.70 6.52—7.71 8.77—8.89	1.36—2.16 3.34—3.79 5.03—5.57 6.72—7.47 ....
$\theta = 89^0$	1.16—2.53 3.31—4.33 5.20—5.90 6.79—8.27	1.53—2.21 3.52—4.02 5.47—5.77 7.15—7.88

shows that for both PCs the total reflection frequency range for TM-polarization is smaller than that of TE-polarization for all the incident angles. For PC2 the difference of total reflection frequency band in TE and TM polarization is much smaller than PC1 in low frequency range. Moreover, in PC2 complete PBG can be achieved because a complete PBG occurs when the total reflected frequency range is almost the same for both polarizations. The reason for enlargement of total omnidirectional reflection bands may be attributed to the phase compensating effect that occurs in left hand materials (LHM) [16].

The analysis has also been made for other value of layer thicknesses in which we have taken $d_1 = 0.7d$ and $d_2 = 0.3d$ while the refractive index contrasts are the same for both types of PCs structures. The corresponding reflection spectras for both polarizations are shown in the Figs. 5(a)–5(b) and 6(a)–6(b) for PC2 and PC1 respectively. In this case too it is observed that omnidirectional reflection bands has been increased by a considerable amount for PC2 in both TE- and TM-mode, which is reported in the Tables 3 and 4 for PC2 and PC1 structures, respectively. The omnidirectional reflection bands for both PCs and for different values of the layer thicknesses are shown by shaded areas in the Figs. 3(a)–3(b) to 6(a)–6(b) respectively.

4. CONCLUSION

In conclusion we have analyzed the reflection properties of one-dimensional photonic crystals composed of alternate layers of ordinary material (OM) and left handed materials (LHM) for different values of layer thicknesses and for the various values of the incident angles. From the analysis it has been found that the proposed structure has very wide range of omnidirectional reflection bands for both polarizations in comparison to the PC structure, which is composed of alternate layers of only ordinary materials with positive index of refraction. The proposed structure also has a complete or absolute band gap, which can be exploited for trapping of light. Moreover, this type of omnidirectional reflector has potential applications in microcavities, antenna substrate and coaxial waveguides etc.

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