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OMNIDIRECTIONAL REFLECTION BANDS IN ONE-DIMENSIONAL PHOTONIC CRYSTAL STRUCTURE USING FULLERENE FILMS

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Abstract—We study the omnidirectional reflection (ODR) in one-dimensional photonic crystal (PC) structures consisting of alternate layers of fullerene-gallium arsenide (GaAs), fullerene-germanium (Ge) and fullerene-telurium (Te). The proposed structures give 100% reflection within a very wide range of wavelength in the visible and in a very narrow portion of near IR region of the EM spectrum. Fullerene (C_{60}) in the form thin film structure is a suitable candidate for the designing the PC structure because alkali-metal doped thin film of fullerene acts as conductor and have almost zero absorption in the wavelength range > 530 nm and near IR region. Also, in this region its dielectric constant has very small dependence on the frequency and can be ignored. Thus being a metallic counter part as well as almost frequency independent dielectric constant and easier fabrication technique it is useful in designing the PC structure. The investigation has also been made for the study the role of ambient medium and effect of number of layers in the formation of ODR.

1. INTRODUCTION

Photonic Crystals (PCs) or Photonic Band Gap (PBG) materials are a new class of optical materials with a periodic modulation in the dielectric constants on the length scale comparable to optical

wavelength. These artificial materials create a range of forbidden frequencies called photonic band gap in which propagation of electromagnetic (EM) wave is completely prohibited. This unique feature of the photonic crystal structures alters dramatically the flow of light and manipulation of photons within the structure and can lead to many potential applications in field of photonics [1–7].

In recent time optical reflectors are one of the most widely used optical devices and a great deal of work has been done on the omnidirectional reflectors [8–14, 23, 24]. Reflectors are mainly of two types: one is metallic and other one is multilayer dielectric reflector. In metallic reflector light can be reflected over a wide range of frequencies for arbitrary incident angles, however, at higher frequencies considerable amount of power is lost 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. The range of reflected frequency of multilayer dielectric reflector can be enhanced by the appropriate selection of the material parameters and layer thickness.

In this paper we study the reflection properties of the one-dimensional (1-d) PC structure consisting alternate layers of fullerene-gallium arsenide (GaAs), fullerene-germanium (Ge) and fullerene-tellerium (Te) The theoretical analysis is based on the transfer matrix method [15]. Recently fullerenes (C_{60}) have attracted much scientific attention due to their novel optical and electrical properties and potential applications such as alkali metal-doped fullerenes become superconductor, while doped thin films act as a conductor. When fullerenes are embedded into lipid membrane then they act as efficient electron acceptors and allow the flow of electron through bilayer [16–21]. In spite of these novel properties, the structural modification of fullerene is very easy which causes the simplicity of the technological treatment. The electronic and optical properties of fullerene films can be engineered by modifying the geometry and the degree of conjugation of carbon superstructure. This property of fullerene may be utilized for the fabrication photonic crystal structure using the fullerene films.

Although three-dimensional (3-D) photonic crystal with complete PBG in the near-infrared (IR) have been fabricated successfully, it is still not easy to fabricate a 3-D PC with a complete PBG. Though there is no complete photonic band gap for one 1-D PC, omnidirectional total reflection can be achieved. The 1-D periodic structures are much easier to fabricate than 2-D and 3-D structures. The existence of total omnidirectional reflection from 1-D system permits one to design extremely cheap and effective photonic insulator tuned to desirable frequency by changing the period of the structure.

2. THEORETICAL ANALYSIS

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 [15]

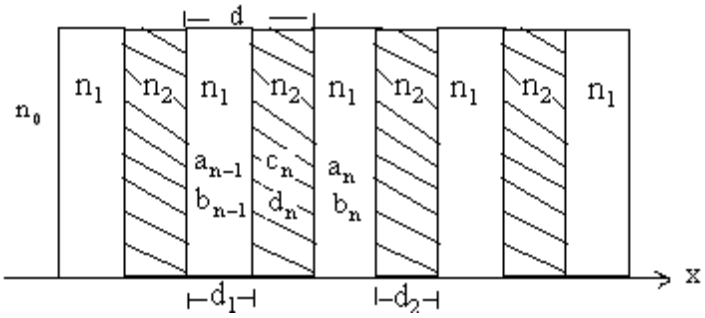

Figure 1. Periodic refractive index profile of the structure having refractive indices n_1 and n_2 respectively.

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 indices of refraction of the system are given as,

$$n(x) = \begin{cases} n_1, & 0 < x < d_1 \\ n_2, & d_1 < x < d \end{cases} \quad \text{with} \quad n(x) = n(x+d). \tag{1}$$

where d_1 and d_2 are the thicknesses of the layers and $d = d_1 + d_2$ is the period of the structure. 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

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

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

where $k_i = \left[\left(\frac{n_i\omega}{c}\right)^2 - \beta^2\right]^{1/2} = \frac{n_i\omega}{c}\cos\theta_i$; θ_i is the ray angle in the ith layer ($i = 1, 2$), β is the propagation constant and n_i is the refractive index 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

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

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

$$A = e^{ik_1d_1}\left[\cos k_2d_2 + \frac{1}{2}i\left(\eta + \frac{1}{\eta}\right)\sin k_2d_2\right]; \tag{5a}$$

$$B = e^{-ik_1d_1}\left[\frac{1}{2}i\left(\eta - \frac{1}{\eta}\right)\sin k_2d_2\right]; \tag{5b}$$

$$C = e^{ik_1d_1}\left[-\frac{1}{2}i\left(\eta - \frac{1}{\eta}\right)\sin k_2d_2\right]; \tag{5c}$$

$$D = e^{-ik_1d_1}\left[\cos k_2d_2 - \frac{1}{2}i\left(\eta + \frac{1}{\eta}\right)\sin k_2d_2\right] \tag{5d}$$

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

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

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

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

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

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

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 existence of omnidirectional photonic band gap or omnidirectional reflection band in one dimensional photonic crystal requires the incident waves to be launched from vacuum or from a low refractive index ambient medium [5]. This is because at the Brewster's angle the TM mode cannot be reflected. From Snell's law we know that $n_0 \sin\theta_0 = n_1 \sin\theta_1$, where n_0 and n_1 are the refractive indices of ambient medium and dielectric layer adjacent to n_0 and θ_0 is the incident angle. We can see that the refracted angle θ_2 is restricted to a certain range. If the maximum restricted angle $\theta_2^{\max} = \tan^{-1}(n_0/n_2)$ is smaller than the internal Brewster's angle $\theta^B = \tan^{-1}(n_1/n_2)$, the incident wave from the outside cannot couple to the Brewster's window, leading to the total internal reflection from all incident angles.

3. RESULTS AND DISCUSSION

In this section we present the numerical analysis of the proposed PC structures and show the omnidirectional reflection bands for both TE- and TM-polarizations. For this computation we consider three cases in which we have taken alternate layers of fullerene-gallium arsenide, fullerene-germanium and fullerene-tellurium respectively. There are two main reasons to choose fullerene films in the designing of photonic crystal structures. These are: (i) as already mentioned that thin film of fullerene acts as a conductor when it is doped with alkali-metal so it is better substitute of metals with the same property and (ii) being a metallic counter part the dielectric constant of the fullerene is complex one and can be expressed as $\varepsilon = \varepsilon' - j\varepsilon''$. The dielectric constant of the fullerene is based on the Kataura's optical data in the visible and near IR region. In this expression the imaginary part (ε'') of the dielectric constant is connected to the absorption and according to Ref. [22] and as shown in the Fig. 2, it is obvious that it has comparatively very low

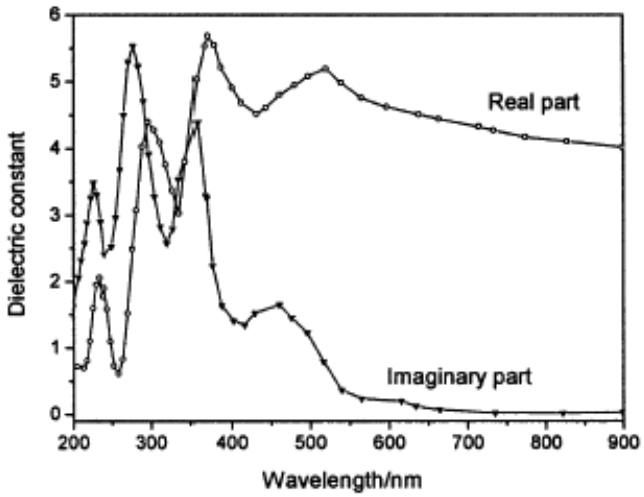

Figure 2. Dielectric constant of C_{60} thin film.

value in the wavelength range above 420 nm and approaches to zero value for the wavelength range lies from 530 nm–1200 nm. Hence the absorption in the fullerene films at the visible and near IR region is not affected and can be neglected and so the dielectric constant of the fullerene film can be treated as real in these regions. Also, there is very small variation in the real part of the dielectric constant and on average it can be taken as 4.4 in the range 530 nm–1200 nm where we have made our numerical analysis.

Now for the numerical computations the value of refractive index for the fullerene film is taken as 2.1 while for GaAs, Ge and Te it is 3.6, 4.2 and 4.6 respectively. The thicknesses of the layers are taken as according to quarter wave stacks condition i.e., $d_1 = \lambda_0/4n_1$ and $d_2 = \lambda_0/4n_2$, thus for $\lambda_0 = 800$ nm and $n_1 = 2.1$ (fullerene film) $d_1 = 95.23$ nm while for GaAs ($n_2 = 3.6$), Ge ($n_2 = 4.2$) and Te ($n_2 = 4.6$) the thickness of layer (d_2) comes out 55.55 nm, 47.62 nm and 43.47 nm respectively, the total number of layers are taken as $N = 25$ in all the three cases. The reflection spectra obtained from equation (8) in three cases are depicted in the Figs. 3–5, for both TE- and TM-polarizations. From the study of these figures it is observed that as the incident angle increases the 100% reflected region of wavelength increases for the TE-mode while it decrease for the TM-mode and at the same time the reflection band is shifted towards the lower wavelength region. The width of the reflection band has larger value for the TE-mode in comparison to the TM-

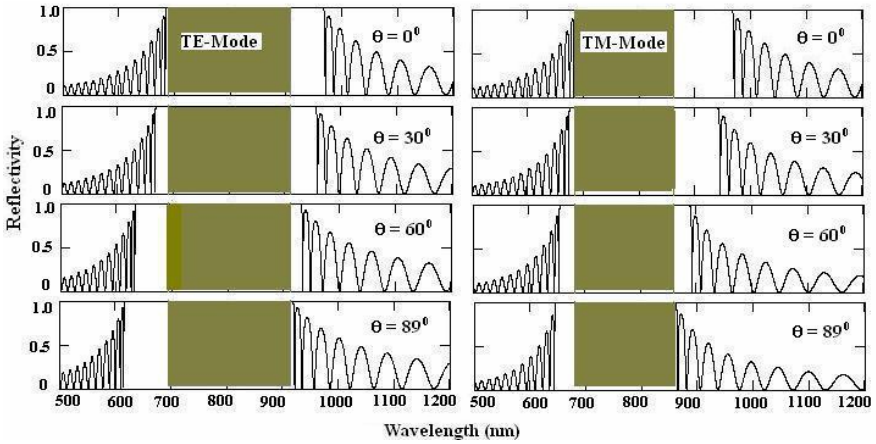

Figure 3. The reflectance spectra for TE- and TM-modes showing the total reflectance region and band width for $n_1 = 2.1$, $n_2 = 3.6$, $d_1 = 952.3\,\text{nm}$, $d_2 = 555.5\,\text{nm}$ and $N = 25$ at the various incident angles.

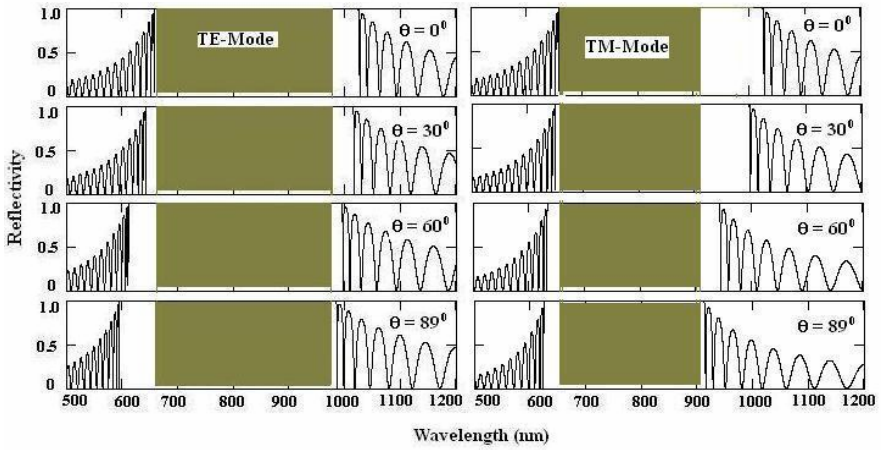

Figure 4. The reflectance spectra for TE- and TM-modes showing the total reflectance region and band width for $n_1 = 2.1$, $n_2 = 4.2$, $d_1 = 952.3\,\text{nm}$, $d_2 = 476.2\,\text{nm}$ and $N = 25$ at the various incident angles.

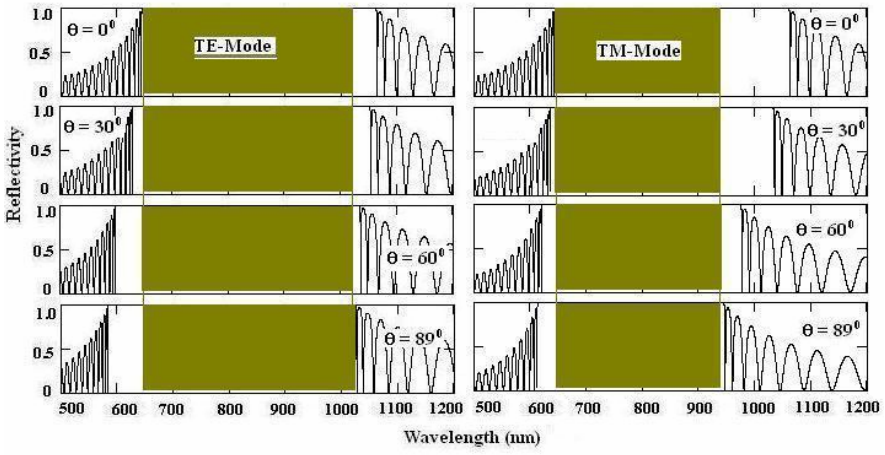

Figure 5. The reflectance spectra for TE- and TM-modes showing the total reflectance region and band width for $n_1 = 2.1$, $n_2 = 4.6$, $d_1 = 952.3\,\text{nm}$, $d_2 = 434.7\,\text{nm}$ and $N = 25$ at the various incident angles.

mode for all the cases considered here. Also, the PC structures having larger value of refractive index contrast have wider reflection bands as usually for the both polarizations. The 100% reflection bands obtained in three different PC structures at different incident angles are shown in the Tables 1–3. The ODR bands in the three PC structures for TE-mode lie from 684.3 nm–915.7 nm (fullerene-GaAs); 657.6 nm–981.7 nm (fullerene-Ge) and 643.1 nm–1022.2 nm (fullerene-Te), while for TM- mode it lie from 684.3 nm–856.6 nm (fullerene-GaAs); 657.6 nm–909.2 nm (fullerene-Ge) and 643.1 nm–941.9 nm (fullerene-Te) respectively. Hence the total reflected wavelength band which is common to the both polarizations and for the entire incident angles lie from 684.3 nm–856.6 nm (fullerene-GaAs); 657.6 nm–909.2 nm (fullerene-Ge) and 643.1 nm–941.9 nm (fullerene-Te) respectively. The region of wavelength band which exists between the lower wavelength edges λ_L at $\theta = 0^\circ$ for TE (or TM) wave and the upper edges of the wavelength (λ_U) at $\theta = 89^\circ$ for TM wave is called omni-PBG. Therefore, the gap $\Delta\lambda = (\lambda_U - \lambda_L)$ to midgap wavelength $\lambda_{mid} = (\lambda_U + \lambda_L)/2$ ratio of omni-PBG increases for the structures having larger value of refractive index contrasts. For fullerene-GaAs structure $\Delta\lambda/\lambda_{mid}$ is equal to 0.223, while for fullerene-Ge it is 0.321 and for fullerene-Te it has value 0.377 respectively.

Moreover in our next study we have seen the effect of ambient medium on Omni-PBG. The analysis shows that the structure will give Omni-PBG if $n_0 < n_1$ and the width of Omni-PBG decreases

Table 1. Total reflectance region (100%) and band width for $n_1 = 2.1$, $n_2 = 3.6$, $d_1 = 95.23\,\text{nm}$, $d_2 = 55.55\,\text{nm}$ and $N = 25$ at the various incident angles for TE- and TM-modes.

Incident Angle (θ_0)	TE-Mode		TM-Mode	
	Reflected Region (nm)	Band Width (nm)	Reflected Region (nm)	Band Width (nm)
0^0	684.3 – 962.7	278.4	684.3 – 962.7	278.4
30^0	657.7 – 951.1	293.4	674.7 – 937.3	262.6
60^0	633.3 – 927.6	294.3	655.2 – 884.3	229.1
89^0	615.5 – 915.7	300.2	645.3 – 856.6	211.3

Table 2. Total reflectance region (100%) and band width for $n_1 = 2.1$, $n_2 = 4.2$, $d_1 = 95.23\,\text{nm}$, $d_2 = 47.62\,\text{nm}$ and $N = 25$ at the various incident angles for TE- and TM-modes.

Incident Angle (θ_0)	TE-Mode		TM-Mode	
	Reflected Region (nm)	Band Width (nm)	Reflected Region (nm)	Band Width (nm)
0^0	657.6 – 1021.1	363.5	657.6 – 1021.1	363.5
30^0	642.3 – 1011.4	369.1	649.4 – 994.3	344.9
60^0	610.8 – 991.7	380.9	632.9 – 938.4	305.5
89^0	594.6 – 981.7	387.1	624.6 – 909.2	284.6

Table 3. Total reflectance region (100%) and band width for $n_1 = 2.1$, $n_2 = 4.6$, $d_1 = 95.23\,\text{nm}$, $d_2 = 43.47\,\text{nm}$ and $N = 25$ at the various incident angles for TE- and TM-modes.

Incident Angle (θ_0)	TE-Mode		TM-Mode	
	Reflected Region (nm)	Band Width (nm)	Reflected Region (nm)	Band Width (nm)
0^0	643.1 – 1057.9	414.8	643.1 – 1057.9	414.8
30^0	628.5 – 1045.7	417.2	635.5 – 1030.0	394.5
60^0	598.5 – 1031.2	432.7	620.3 – 972.1	351.8
89^0	583.1 – 1022.2	439.1	612.6 – 941.9	329.3

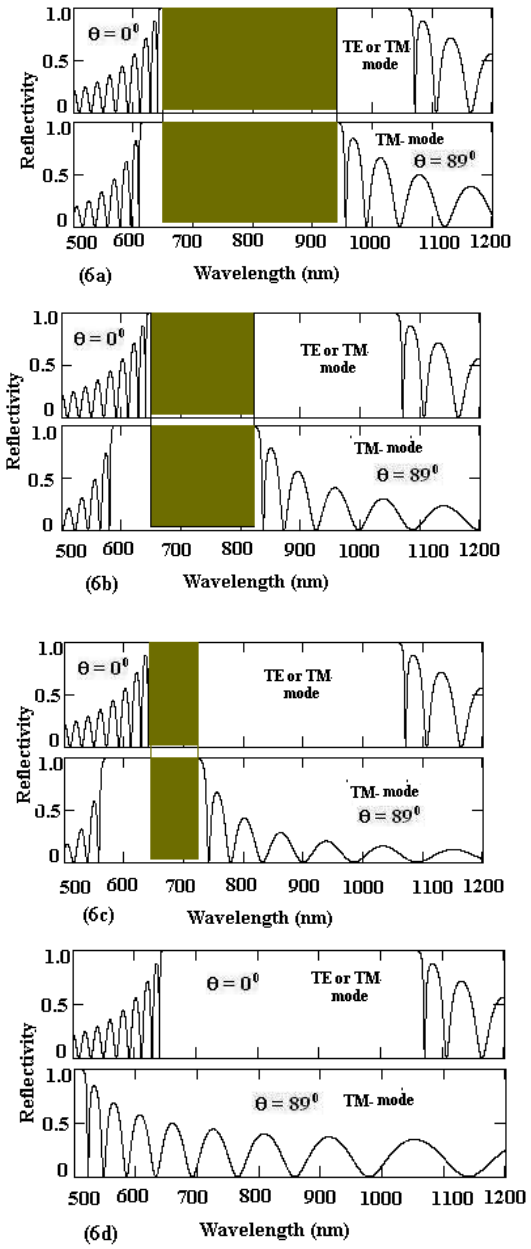

Figure 6. The reflection curves and illustrate the Omni-PBG region for $n_1 = 2.1$, $n_2 = 4.6$, $d_1 = 952.3\,\text{nm}$, $d_2 = 434.7\,\text{nm}$ and $N = 15$ where ambient medium has the value of refractive index $n_0 = 1.0, 1.38, 1.6$ and 2.06.

as n_0 approaches to n_1. The width of the ODR band for fullerene-Te structure having layer thickness $d_1 = 95.23\,\text{nm}$ and $d_2 = 43.47\,\text{nm}$ and number of layers 15 for the different values of ambient medium $n_0 = 1.0, 1.38, 1.6$ and 2.06 are given as 644.1 nm–938.4 nm, 644.1 nm–818.0 nm and 644.1 nm–716.5 nm respectively. But when $n_0 = 2.06$ i.e., close to the value of lower refractive index (n_1) the Omni-PBG completely disappears. Thus from these studies it is concluded that the ambient medium has important role in the formation of ODR band or Omni-PBG as shown in the Figs. 6a–6c respectively, by the shaded region whereas Fig. 6d shows the reflection spectra for $n_0 = 2.06$ where Omni-PBG completely disappears. Finally we have studied the effect of number layers on the ODR. The study shows that as we increase the number of layers the reflection band becomes wider and wider for the same value of refractive index contrast and for the same thickness which is shown in the Fig. 7. Thus in final conclusion, we observe that

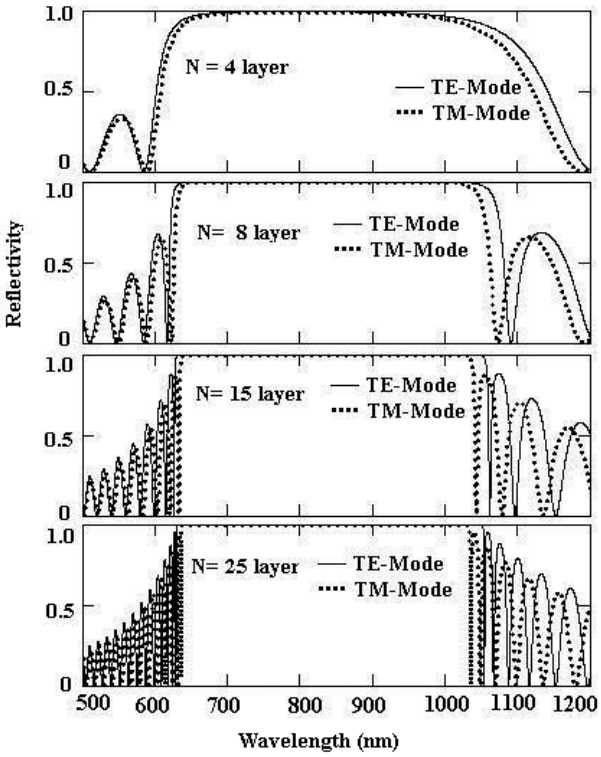

Figure 7. The reflectance curve for $n_1 = 2.1$, $n_2 = 4.6$, $d_1 = 952.3\,\text{nm}$, $d_2 = 434.7\,\text{nm}$ and $N = 4, 8, 15$ and 25 and for $\theta_0 = 30^\circ$.

the fullerene based photonic crystal structure can be used as good candidate for the complete inhibition of transmission of frequency in the wide range of visible region and a very narrow range of the near IR region for any oblique incidence. Hence the proposed structure can be used as an omnidiretional reflector in the field of optical technology.

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