Progress In Electromagnetics Research M, Vol. 38, 37–44, 2014

Investigation of Ultra-Wide Reflection Bands in UV Region by Using One-Dimensional Multi Quantum Well Photonic Crystal

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Abstract—Enhancement of the reflection bands in ultraviolet region by using one-dimensional multi quantum well (MQW) photonic crystal (PC) structure has been investigated theoretically. The proposed structure is composed of three $MgF_2/SrTiO_3$ MQWs. The range of reflection band is investigated from the reflectance spectra of the one-dimensional MQW photonic crystal structure obtained by Transfer Matrix Method (TMM). From the numerical analysis it is observed that a range of reflection band for a single MQW PC is very narrow though it increases as the thickness of layers increases. But when three MQWs of $MgF2/SrTiO_3$ are used we get much enlarged reflection band covering the range 119.8 nm–311.3 nm (reflectivity $> 99\%$) with bandwidth 191.5 nm, for normal incidence. Further, we see that when the angle of incidence is increased, the width of reflection band increases in case of TE wave with a decrease for TM wave, because this omnidirectional reflection (ODR) band is very much narrow in UV region. We have computed ODR band upto incidence angle 50° for single as well as combined MQW PC. Analyzing the reflectance curve for incidence angle up to 50° for both TE and TM polarizations we find that by applying the combined MQW PC, omnidirectional reflection band increases significantly in comparison to single MQW structure. The proposed MQW photonic crystal structure is very useful in designing ultraviolet shielding for drugs, ultraviolet reflector for protecting damage of DNA and in skin diseases especially for skin cancer.

1. INTRODUCTION

During the past few years photonic crystals (PCs), which are structured materials with periodically modulated dielectric function and showing photonic band gap (PBG), have attracted considerable interest of scientists and engineers. The propagation of electromagnetic waves in these structures is prohibited in a certain range of frequency or wavelength called photonic band gaps. Due to their novel optical properties to control and manipulate the flow of light, PC structures have many potential applications in optoelectronic and photonic devices [1–6]. According to the direction of modulation in refractive index, photonic crystals are classified as one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D). The 1D PC structures are attractive and studied most, because their production is more feasible at any wavelength, and their analytical and numerical calculations are comparatively simple. In addition, it is very cost effective and has numerous applications. By introducing a defect into 1DPC structure one can produce a micro cavity or tunneling mode inside the band gap [7–10]. This can be done simply by removing a single layer from the multilayer or introducing other layers of different refractive indices or thicknesses in the normal structure. In the case of 2D PC structure, introduction of defect (called line defect) generates wave guiding [11]. One of the most important applications of 1D PC is omnidirectional reflector (ODR), generally called as a Bragg mirror or optical mirror. A great deal of work has been reported by various researchers [12–16]. 1D PC as an optical mirror has been studied widely in visible, infrared, microwave, millimeter and terahertz region by many authors [14–18].

Received 23 June 2014, Accepted 31 July 2014, Scheduled 13 August 2014
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However, in the wavelength region less than visible, i.e., in ultraviolet (UV) region, few research papers have been reported [19–22], because the materials used for study in UV region show high absorption and unstable refractive index due to prolonged irradiation with UV light.

In this paper, we propose a model to enhance the range of reflection band in UV region, by using one-dimensional multi quantum well (MQW) photonic crystal structure, for the normal as well as oblique incidence. For the proposed multi quantum well, we choose MgF_2 and $SrTiO_3$ as low and high refractive index materials, because these materials have very low absorption coefficient in the ultraviolet region (100 nm—300 nm) which can be ignored [22]. The reflection band is investigated from the reflectance spectra of 1D MQWs PC structure obtained by the Transfer Matrix Method (TMM). Numerically we will show that the range of reflected wavelength band increases significantly by using MQWs PC structure in comparison to single PC structure.

2. THEORETICAL MODEL AND FORMULATIONS

Figure 1 illustrates the schematic view of 1D MQW PC structure. In Figure 1, A, C and E represent MgF_2 (low refractive index n_1) while B, D and F represent $SrTiO_3$ (high refractive index material n_2). The multi quantum well has the form $air/(AB)^N/(CD)^N/(EF)^N/substrate$, where N is the number of periodic layers of each MQW structure. The thicknesses of the unit cell in MQWs are d_1, d_2 and d_3 where $d_1 = d_A + d_B$, $d_2 = d_C + d_D$ and $d_3 = d_E + d_F$, respectively.

The periodic multilayered structure consists of alternate layers of high and low refractive indice along the x-axis and placed between semi-infinite media of refractive indices n_0 (refractive index of the incident medium) and n_t (refractive index of the substrate). In order to investigate the reflection band of the structure, we use transfer matrix method (TMM). The characteristics matrices for the transverse electric (TE), i.e., for s-polarized and for the transverse magnetic (TM), i.e., p-polarized waves can be given as [23, 24]

$$M_i = \begin{bmatrix} \cos\beta_i & \dfrac{1}{jq_i}\sin\beta_i \\ -jq_i\sin\beta_i & \cos\beta_i \end{bmatrix} \tag{1}$$

where $q_i = n_i \cos\theta_i$, $(i = 1, 2)$ for the TE wave and $q_i = \cos\theta_i/n_i$ for the TM wave, $\beta_i = \frac{2\pi}{\lambda} n_i d_i \cos\theta_i$, θ_i is the ray angle inside the layer of refractive index n_i, d_i the thickness of the layers, and λ the wavelength in the incidence medium.

Now the total characteristics matrix for the N period of system is given by

$$M = (M_i)^N \tag{2}$$

The reflection coefficient of the multilayered structure for TE (s-polarized) and TM (p-polarized) waves

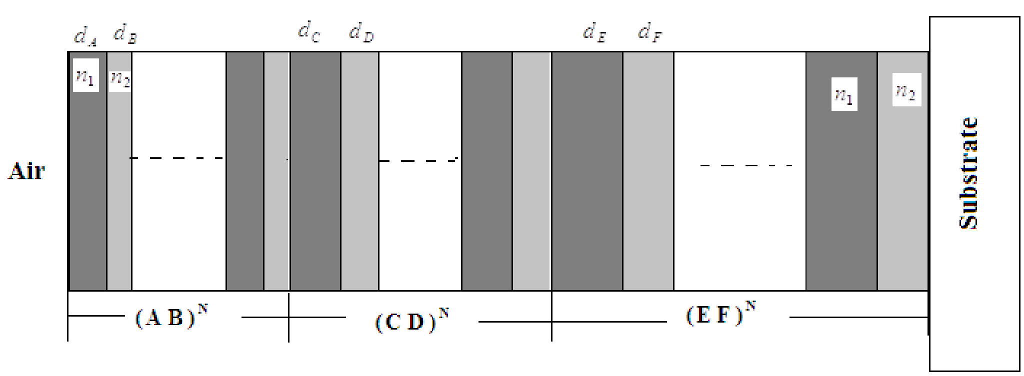

Figure 1. Schematic representation of one-dimensional multi quantum well photonic crystal structure.

are given by [23, 24]

$$r(s) = \frac{(M_{11} + q_t(s)M_{12})\,q_0(s) - (M_{21} + q_t(s)M_{22})}{(M_{11} + q_t(s)M_{12})q_0(s) + (M_{21} + q_t(s)M_{22})} \tag{3}$$

$$r(p) = \frac{(M_{11} + q_t(p)M_{12})\,q_0(p) - (M_{21} + q_t(p)M_{22})}{(M_{11} + q_t(p)M_{12})q_0(p) + (M_{21} + q_t(p)M_{22})} \tag{4}$$

where M_{11}, M_{12}, M_{21}, M_{22} are the elements of the total characteristic matrix of the N period multilayer structures. The values of q_0 and q_t for TE (s) and TM (p) polarized waves are given as

$$q_0(s) = n_0 \cos\theta_0; \quad q_t(s) = n_t \cos\theta_t \tag{5}$$

$$q_0(p) = \cos\theta_0/n_0; \quad q_t(p) = \cos\theta_t/n_t \tag{6}$$

Here n_0 and n_t are the refractive indices of the incident medium and substrate whereas θ_0 and θ_t are angles of incidence in these media.

Finally, one can obtain the reflection band of the multilayered structure in case of s- and p-polarized waves by using the expression:

$$R(s,p) = |r(s,p)|^2 \tag{7}$$

3. NUMERICAL RESULTS AND DISCUSSIONS

In this section we present numerical results of the reflectance spectra in UV region. For the proposed multi quantum well we choose MgF_2 ($n_1 = 1.39$) and $SrTiO_3$ ($n_2 = 2.437$) as low and high refractive

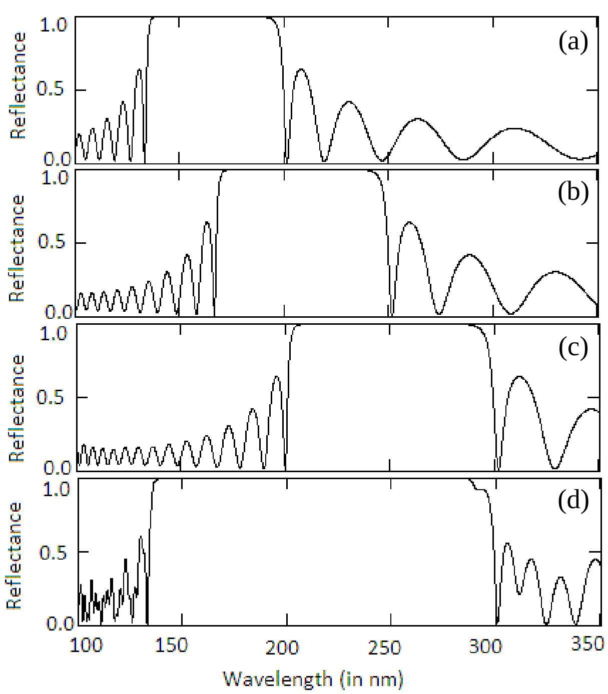

Figure 2. Reflectance spectra of a photonic quantum well structure at normal incidence for (a) $(AB)^{10}$, (b) $(CD)^{10}$, (c) $(EF)^{10}$, and (d) $(AB)^{10}/(CD)^{10}/(EF)^{10}$ having thicknesses $d_A = 28.8$ nm, $d_B = 16.4$ nm, $d_C = 36$ nm, $d_D = 20.5$ nm, $d_E = 43.2$ nm, and $d_F = 24.6$ nm, respectively.

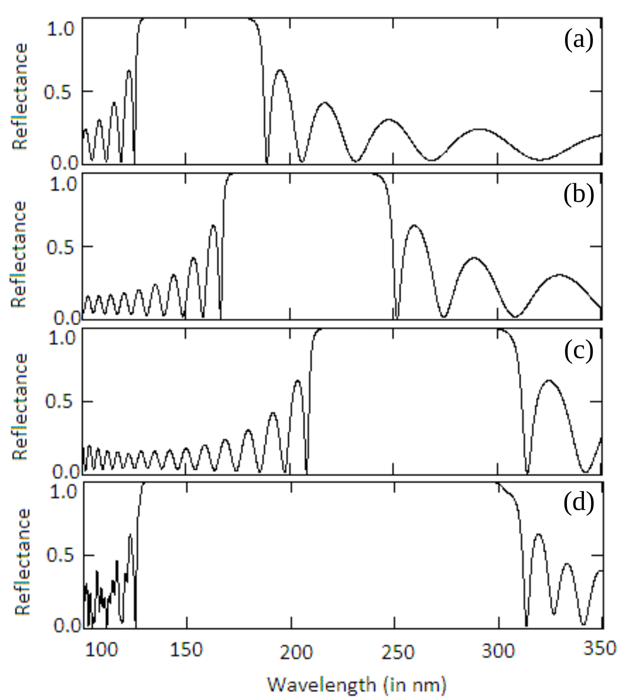

Figure 3. Reflectance spectra of a photonic quantum well structure at normal incidence for (a) $(AB)^{10}$, (b) $(CD)^{10}$, (c) $(EF)^{10}$ and (d) $(AB)^{10}/(CD)^{10}/(EF)^{10}$ having thicknesses $d_A = 27$ nm, $d_B = 15.4$ nm, $d_C = 36$ nm, $d_D = 20.5$ nm, $d_E = 45$ nm, and $d_F = 25.6$ nm, respectively.

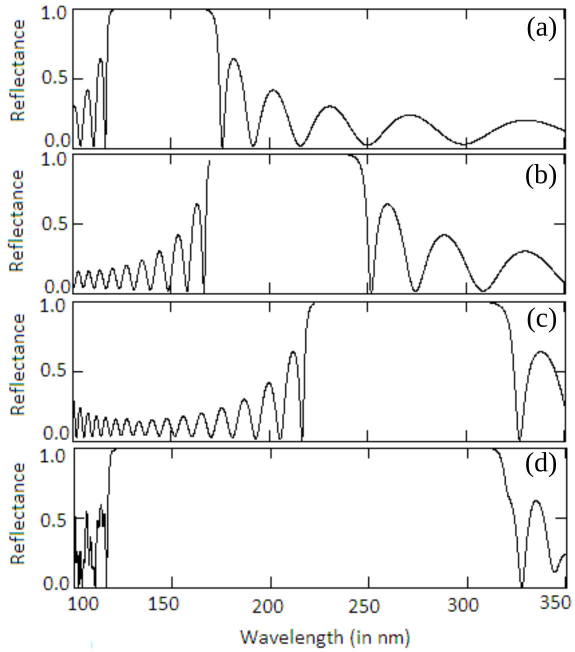

Figure 4. Reflectance spectra of a photonic quantum well structure for (a) $(AB)^{10}$, (b) $(CD)^{10}$, (c) $(EF)^{10}$, and (d) $(AB)^{10}/(CD)^{10}/(EF)^{10}$ and for thicknesses $d_A = 25.2\,\text{nm}$, $d_B = 14.3\,\text{nm}$, $d_C = 36\,\text{nm}$, $d_D = 20.5\,\text{nm}$, $d_E = 46.7\,\text{nm}$, and $d_F = 26.7\,\text{nm}$, respectively.

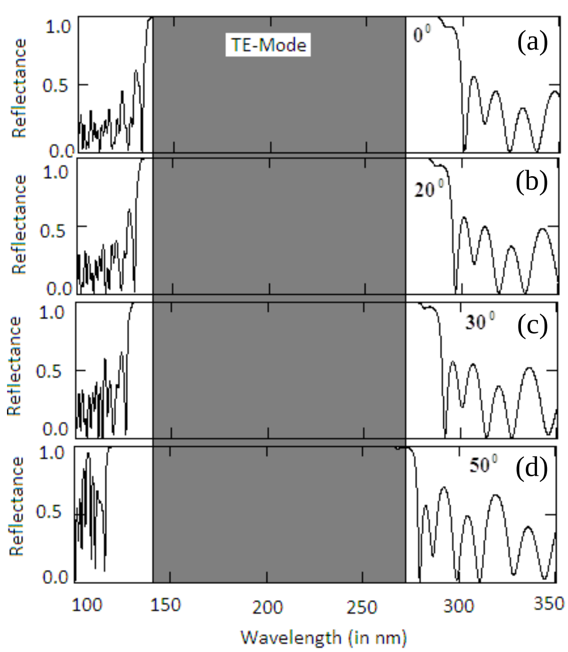

Figure 5. TE-reflectance spectra of a photonic quantum well structure $(AB)^{10}/(CD)^{10}/(EF)^{10}$ for incidence angles (a) 0°, (b) 20°, (c) 30°, and (d) 50° having thicknesses $d_A = 28.8\,\text{nm}$, $d_B = 16.4\,\text{nm}$, $d_C = 36\,\text{nm}$, $d_D = 20.5\,\text{nm}$, $d_E = 43.2\,\text{nm}$, and $d_F = 24.6\,\text{nm}$, respectively.

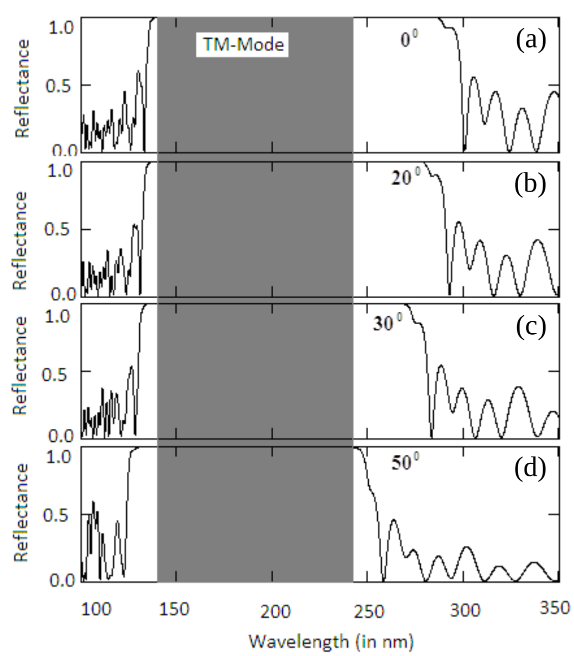

Figure 6. TM-reflectance spectra of a photonic quantum well structure $(AB)^{10}/(CD)^{10}/(EF)^{10}$ for incidence angles (a) 0°, (b) 20°, (c) 30°, and (d) 50° having thicknesses $d_A = 28.8\,\text{nm}$, $d_B = 16.4\,\text{nm}$, $d_C = 36\,\text{nm}$, $d_D = 20.5\,\text{nm}$, $d_E = 43.2\,\text{nm}$, and $d_F = 24.6\,\text{nm}$, respectively.

index materials, because these materials have very low absorption coefficient in the ultraviolet region (100 nm—300 nm) which can be ignored [22]. The reflectance curves of MQWs, at normal incidence angle, for different thicknesses of the unit cell have been investigated. The thicknesses of the different MQWs are taken as $d_A = d_C - pd_C$, $d_B = d_D - pd_D$, $d_E = d_C + pd_C$, and $d_F = d_D + pd_D$, where d_C and d_D are the thicknesses of layers corresponding to $(CD)^N$ MQW structures, and p is fraction of change in thickness of layers. The thickness of middle quantum well $(CD)^N$ is selected according to quarter wave stack condition $n_1 d_C = n_2 d_D = \frac{\lambda_0}{4}$ where λ_0 is the central wavelength which we take here 200 nm. The fractional changes in thickness of layers are taken as $p = 0.20$, 0.25 and 0.30, respectively. First we calculate the reflectance spectra of single MQWs $(AB)^N$, $(CD)^N$, $(EF)^N$, respectively for $N = 10$ shown in Figures 2(a)–(c). In this case, the thicknesses of the layers ($p = 0.20$) are taken as $d_A = 28.8$ nm, $d_B = 16.4$ nm, $d_C = 36$ nm $d_D = 20.5$ nm, $d_E = 43.2$ nm, and $d_F = 24.6$ nm, respectively. The reflectance curves show that reflection band in single quantum well is very narrow and located at 137.3 nm–191.6 nm, 171.7 nm–239.4 nm, and 206 nm–287.5 nm, respectively, but when three quantum wells are used, the range of reflection band gets enlarged and covers the range 137.3 nm–287.5 nm with band width 150.2 nm, shown in Figure 2(d). When the thickness of the layers in MQW PC structure is varied by 0.25 and 0.30 with respect to the middle MQW structure, the reflected wavelength band increases significantly. For $p = 0.25$, MQWs have thicknesses as $d_A = 27$ nm, $d_B = 15.4$ nm, $d_C = 36$ nm, $d_D = 20.5$ nm, $d_E = 45$ nm, and $d_F = 25.6$ nm, respectively. In this case, the reflected wavelength covers the range 128.7 nm–298.9 nm with bandwidth 170.2 nm, shown in Figures 3(a)–(d). The reflectance curves of MQW (for $p = 0.30$), having thicknesses as $d_A = 25.2$ nm, $d_B = 14.3$ nm, $d_C = 36$ nm, $d_D = 20.5$ nm, $d_E = 46.7$ nm, and $d_F = 26.7$ nm, respectively, illustrated in Figures 4(a)–(d). In this case, the overlapped region of reflection band due to each single MQW covers the range 119.8 nm–311.3 nm. The bandwidth of MQW structure in this case is found to be 191.5 nm. Comparing the three MQWs having $p = 0.20$, 0.25 and 0.30, it is found that photonic band gap increases from 150.2 nm to 170.2 nm (for $p = 0.20$ to 0.25) and from 170.2nm to 191.5 nm (for $p = 0.25$ to 0.30). This indicates

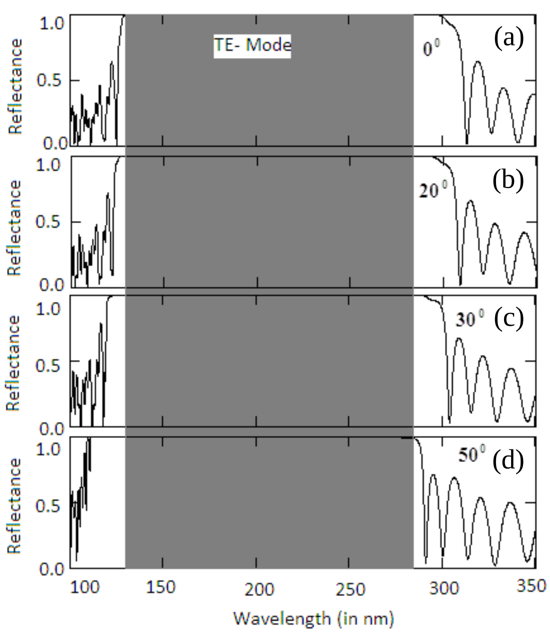

Figure 7. TE-reflectance spectra of a photonic quantum well structure $(AB)^{10}/(CD)^{10}/(EF)^{10}$ for incidence angles (a) 0°, (b) 20°, (c) 30°, and (d) 50° having thicknesses $d_A = 27$ nm, $d_B = 15.4$ nm, $d_C = 36$ nm, $d_D = 20.5$ nm, $d_E = 45$ nm, and $d_F = 25.6$ nm, respectively.

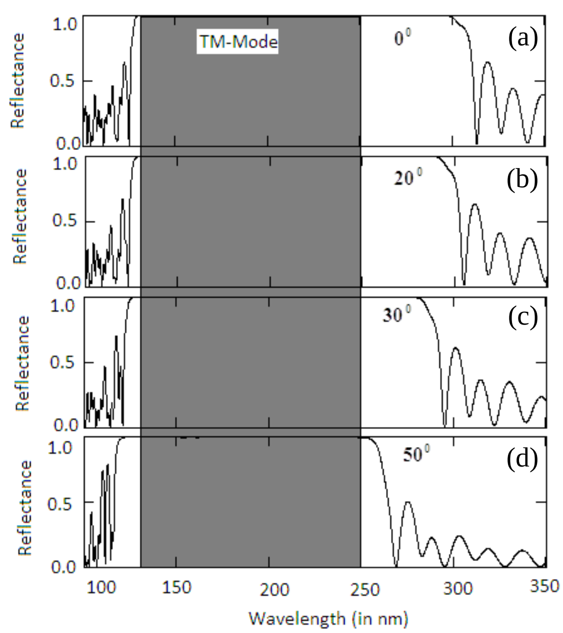

Figure 8. TM-reflectance spectra of a photonic quantum well structure$(AB)^{10}/(CD)^{10}/(EF)^{10}$ for incidence angles (a) 0°, (b) 20°, (c) 30°, and (d) 50° having thicknesses $d_A = 27$ nm, $d_B = 15.4$ nm, $d_C = 36$ nm, $d_D = 20.5$ nm, $d_E = 45$ nm, and $d_F = 25.6$ nm, respectively.

that that band gap enhances approximately 15% to 36 %, when the thickness of the unit cell is varied from $p = 0.20$ to 0.25 and from $p = 0.25$ to 0.30. Further increase in variation in thickness of layers does not increase the range of photonic band gap because reflected wavelength region of single MQW does not overlap to each other. Thus we see that application of combined MQW can broaden the width of reflection band effectively.

Now we analyze reflectance spectra of MQW at oblique incidence (at 20°, 30° and 50°) for both polarizations (TE- and TM-polarizations). The range of reflection band or photonic band gap common to both polarizations at all possible incidence angles (0° to 90°) is called omnidirectional reflection (ODR) band. It is very difficult to achieve broad ODR band in UV region by using a single MQW PC structure. One of the reasons behind this is narrower range of UV than other parts of EM spectrum (visible or infrared). Secondly, lower and higher band edges of TM-reflection band shift slowly towards lower and higher sides of the wavelength compared with TE-reflection band with the increase in incidence angle.

Figures 5, 7, 9 and 6, 8, 10 depict the reflectance spectra of combined MQWs for $p = 0.20$, 0.25 and 0.30 at incidence angles 0°, 20°, 30° and 50° for TE- and TM-polarizations, respectively. From the study of these reflectance curves it is found that with the increase in incident angle the width of TE-reflection band increases while TM-reflection band decreases. We calculate the reflectance spectra up to 50° because when incidence angle increases from 50°, overlapping portion of the PBG is disturbed. The ODR band (up to 50°) of combined MQWs for $p = 0.20$ covers the range 137.3 nm–243 nm with bandwidth 85.7 nm. The range of ODR band and its width increases when the variation in thickness increases. For $p = 0.25$, the range of ODR band is obtained as 128.7 nm–254.0 nm with bandwidth 125.3 nm, while for $p = 0.30$ it covers the ranges 119.8 nm–14 137.3 nm and 156.9 nm–267.1 nm with bandwidths 22.2 nm and 100.8 nm, respectively. The actual bandwidth in this case is 123.0 nm, but approximately we can predict it as 119.8–267.1 nm (with bandwidth 147.3 nm).

Finally, we show the ODR band for single MQW having fractional change in thickness as $p = 0.30$ and $N = 30$ layers which is presented in Figures 11 and 12 for TE- and TM-polarizations. Analyzing

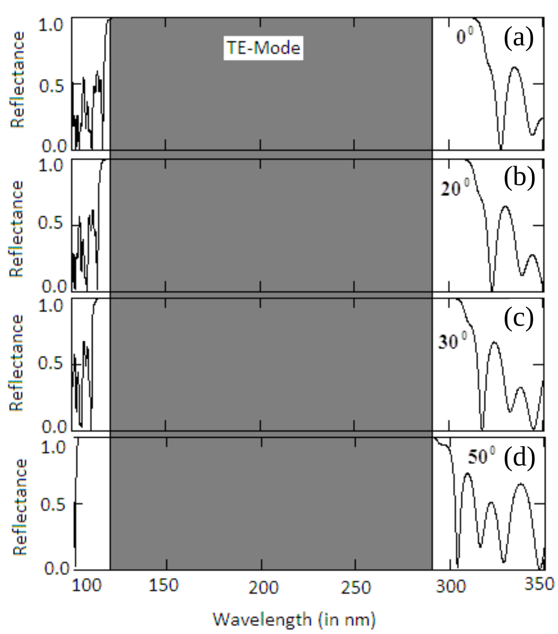

Figure 9. TE-reflectance spectra of a photonic quantum well structure $(AB)^{10}/(CD)^{10}/(EF)^{10}$ for incidence angles (a) 0°, (b) 20°, (c) 30°, and (d) 50° having thicknesses $d_A = 25.2$ nm, $d_B = 14.3$ nm, $d_C = 36$ nm, $d_D = 20.5$ nm, $d_E = 46.7$ nm, and $d_F = 26.7$ nm, respectively.

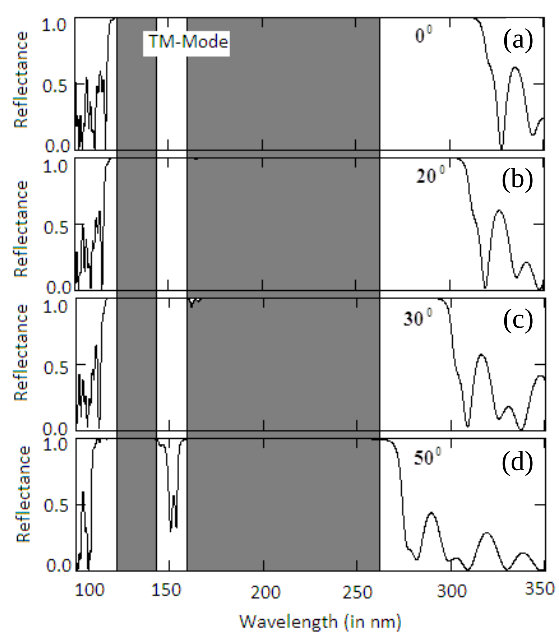

Figure 10. TM-reflectance spectra of a photonic quantum well structure $(AB)^{10}/(CD)^{10}/(EF)^{10}$ for incidence angles (a) 0°, (b) 20°, (c) 30°, and (d) 50° having thicknesses $d_A = 25.2$ nm, $d_B = 14.3$ nm, $d_C = 36$ nm, $d_D = 20.5$ nm, $d_E = 46.7$ nm, and $d_F = 26.7$ nm, respectively.

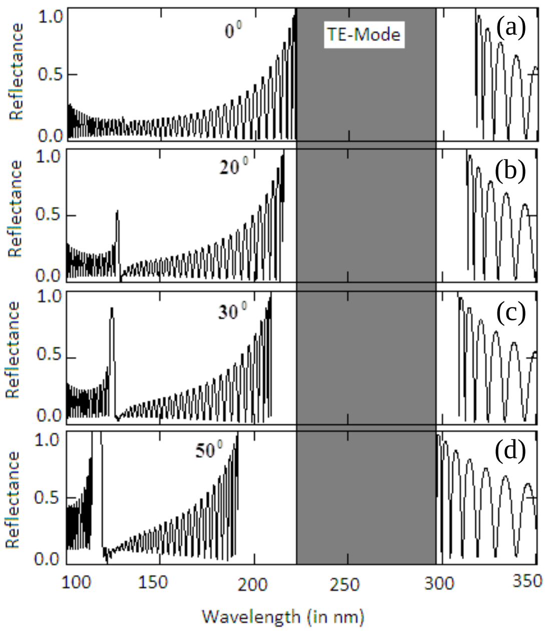

Figure 11. TE-reflectance spectra of a photonic quantum well structure $(EF)^{30}$ for incidence angles (a) 0°, (b) 20°, (c) 30°, and (d) 50° having thicknesses $d_E = 46.7$ nm and $d_F = 26.7$ nm.

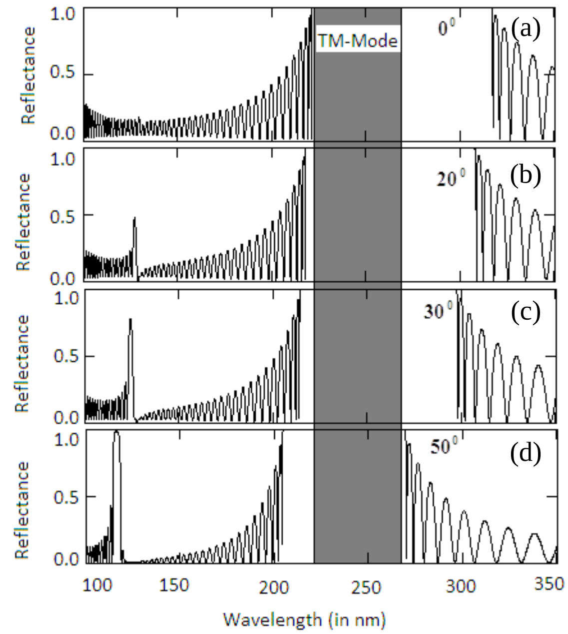

Figure 12. TM-reflectance spectra of a photonic quantum well structure $(EF)^{30}$ for incidence angles (a) 0°, (b) 20°, (c) 30°, and (d) 50° having thicknesses $d_E = 46.7$ nm and $d_F = 26.7$ nm.

these curves we see that ODR bands, the range of reflection band, which is common to both polarizations, cover the range 220.8 nm–268.5 nm, with bandwidth 47.7 nm, which appears very narrow. Hence we can conclude that by applying the combined MWQ the range of reflection band (> 99%) in UV region can be enlarged to significant amount. Further ODR bands get enhanced appreciably in comparison with single MQW having the same variation in thickness of unit cell and number of periodic layers.

4. SUMMARY

In conclusion, theoretical investigation of enhancement of the reflection bands in ultraviolet region by using one-dimensional multi quantum well (MQW) photonic crystals has been presented and discussed. The proposed structure is composed of three $MgF_2/SrTiO_3$ MQWs, and the reflection spectrum is obtained by employing the transfer matrix method (TMM). From the analysis of the proposed structure it is observed that by applying the combination of multi quantum well structure with a suitable value of thickness of unit cell in each case, one gets very enlarged range of reflection bands. The range of reflection bands can be further increased by increasing the thickness of the unit cell. We have also investigated the ODR band up to incident angle 50° and found that there is significant enhancement in ODR band by using three MQWs in comparison with single MQW structure for the same number of layers. The proposed MQW photonic crystals can be used to design the ultraviolet reflector to protect the DNA from damage, in ultraviolet shielding for drugs, in skin diseases especially for skin cancer and in the detection of charged particle.

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