Design And Evaluation Of Distributed Bragg Reflector From 1D Photonic Crystal Using Zemax And Teraplot

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***Abstract*— A theoretical investigation in the field of photonic crystals is presented through the design of "omnidirectional reflector ". Quarter wave optical thickness multilayer is well-known idea widely used to design a high reflector and one-dimensional photonic crystal. This idea was developed to establish Distributed Bragg reflector. TiO_2 and SiO_2 are chosen as a high and low dielectric materials deposited on BK7 glass. Results indicate that the design and evaluation of wideband omnidirectional reflector from 1D PC can be easily established when ZEMAX follows by Teraplot software were adopted .**

Keywords—Photonic Crystal, Distributed Bragg reflector, omnidirectional reflector, ZEMAX, Teraplot software.

1. Introduction

The alternating sequence of high and low refractive index layers represents a dielectric lattice and can therefore be regarded as a one-dimensional (1D) photonic crystal, with more than one dimension, know as called *photonic crystals* as a new class of optical materials[1,2]. Similar to electron propagation in atomic crystals, the periodic modulation of the dielectric creates a potential landscape which determines the propagation directions of photons within the material as a function of frequency [2]. These materials are based on the interaction between an optical field and materials exhibiting periodicity on the scale of wavelength that affects the motion of photons in much the same way that ionic lattices affect electrons in solids. The main feature of photonic crystals is that they can prohibit the propagation of electromagnetic waves within a certain frequency range called photonic band gap (PBG) [1,3]. One-dimensional periodic structures with alternating layers of low and high refractive indices can exhibit omnidirectional reflection (ODR) , which means a high reflection at any polarization and any incident angle over a certain spectral range[4,5]. One-dimensional photonic band gaps are formed in the dielectric multilayer if optical constants and thicknesses of films meet the Bragg resonance condition. This means that a pair of adjacent layers should have a total optical thickness of one half of design wavelength[4-6] . These photonic band gaps display themselves as high intensity reflection or transmission bands in the optical spectra of the dielectric multilayer. Multilayer dielectric mirrors are used primarily to reflect a narrow range of frequencies incident from a particular angle or particular angular range [4,7]. A dielectric mirror, also known as a Bragg mirror, is a type of mirror coatings usually based on the periodic layer system composed from two materials, one with a high index and the other low index material with thickness of quarter wavelength at normal incidence. By careful choice of the type and thickness of the dielectric layers, one can design ultra-high mirrors with reflectivity values of 99.999% or better over a narrow range of wavelengths called *band-stop* [8] . A Bragg mirror is also known as a *distributed Bragg reflector* (DBR). It has a high reflectivity around a particular wavelength defined as design wavelength. The range of wavelengths that are reflected is called the photonic stop band[8]. Within this range of wavelengths, light is "forbidden" to propagate in the structure. Recently , DBR with a complete TE and TM band gap was achieved [9]. Distributed Bragg reflectors are critical components in vertical cavity surface emitting lasers(VCSEL's) and other types of narrow-line width laser diodes[10,11] such as distributed feedback (DFB) lasers and distributed bragg reflector (DBR) lasers. They are also used to form the cavity resonator (or optical cavity) in fiber lasers and free electron lasers [12], spontaneous emission [13], high-reflecting omni-directional mirrors [14,15], and low-loss-waveguiding [16], all-optical transistors, amplifiers, routers photonic integrated circuits, optical computing [17].In this paper , reflectance of 1D PC of periodic structure was studied with the aid of Zemax software follows by Teraplot as graphical method . Further, the effect of construction parameters and angle of incident of light also investigate.

2.Theoretical Analysis

When light obliquely incident on optical coating ,the electric E and magnetic components H for input and output were related by a Transfer matrix(TM) of the thin film ,

$$\begin{pmatrix} E_a \\ H_a \end{pmatrix} = \begin{pmatrix} \cos\delta & i\sin\delta/\eta_1 \\ i\eta_1 \sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} E_b \\ H_b \end{pmatrix} \qquad (1)$$

Where $\delta = 2\pi\left(\frac{n_1 d \cos\theta_1}{\lambda}\right)$, δ – is the phase thickness ,"d" is the geometric thickness of the layer, θ_1 is the angle of propagation in the second medium. The effective index η have different forms for TE and

TM polarized light ,i.e η_0 and η_1 are the effective index (optical admittance) for the two media, they are different for TE and TM polarized light which are:

$$\eta_{TE} = n\cos\theta \tag{2}$$

$$\eta_{TM} = n/\cos\theta \tag{3}$$

Equation (1) can be extended to the general case of an assembly of *q* layers shown in Fig (2).

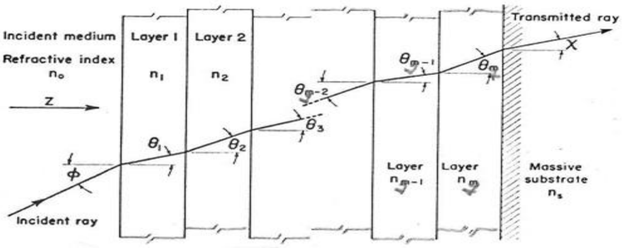

Fig.1: Notation for a multilayer-model [18]

Where *Φ* is an angle of incident and X is an angle of transmitted. The characterize matrix is then simply the product the individual matrices taken in the correct order i.e.

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left\{ \prod_{r=1}^{q} \begin{bmatrix} \cos\delta_r & (i\sin\delta_r)/\eta_r \\ i\eta_r\sin\delta_r & \cos\delta_r \end{bmatrix} \right\} \begin{bmatrix} 1 \\ \eta_m \end{bmatrix} \tag{4}$$

In term of equation (4) , the transmission and the reflection intensities of the high including the amplitude and the phase change of the electric field under all incidence condition ,can be precisely calculated as function of the wavelength [18] and angle , The reflectance for TE and TM polarization is :

$$R = \left(\frac{\eta_{0\Lambda} - \eta_\Lambda}{\eta_{0\Lambda} + \eta_\Lambda}\right)\left(\frac{\eta_{0\Lambda} - \eta_\Lambda}{\eta_{0\Lambda} + \eta_\Lambda}\right)^* \tag{5}$$

Where Λ is a TE and TM polarization, In this work ,ZEMAX was adopted which the analysis of optical performance already based on the elegant method , the transfer matrix method (TMM) [7].

A high reflectance coating can be designed by using dielectric quarter-wave stack of alternate high- and low refractive index materials. If n_H and n_L are the indices of the high- and low-index layers and if the stack is arranged, the high-index layers are outermost at both sides. The transformation matrix for a stack of N pairs of quarter-wave layers of high and low refractive index materials can be expressed in the form:

$$[M] = [M_H]\,[M_L] \tag{6}$$

Where

$$[M] = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} \cos\delta_H & i\sin\delta_H/\eta_H \\ i\eta_H\sin\delta_H & \cos\delta_H \end{pmatrix} \begin{pmatrix} \cos\delta_L & i\sin\delta_L/\eta_L \\ i\eta_L\sin\delta_L & \cos\delta_L \end{pmatrix} \tag{7}$$

At quarter wavelength

$$[M] = \begin{pmatrix} (-\eta_L/\eta_H)^S & 0 \\ 0 & (-\eta_H/\eta_L)^S \end{pmatrix} \tag{8}$$

Maximum reflectance for even layers (2S) and odd layers (2S+1) are then :

$$R_{\Lambda\,Max} = \left(\frac{(\eta_o/\eta_S)(\eta_L/\eta_H)^{2S} - 1}{(\eta_o/\eta_S)(\eta_L/\eta_H)^{2S} + 1} \right)_\Lambda \tag{9}$$

$$R_{\Lambda\,Max} = \left(\frac{1 - (\eta_H/\eta_L)^{2S}(\eta_H^2/\eta_o\eta_S)}{1 + (\eta_H/\eta_L)^{2S}(\eta_H^2/\eta_o\eta_S)} \right)_\Lambda \tag{10}$$

With a band width Δg for different polarization states are[10],

$$\Delta g_\Lambda = \frac{2}{\pi}\sin^{-1}\left[\frac{(\eta_H/\eta_L) - 1}{(\eta_H/\eta_L) + 1}\right]_\Lambda \tag{11}$$

The condition for optimum reflection (Bragg condition) from a low-and a high-refractive index layer pair at a given angle and polarization is that the optical thickness be one-half wavelength at the center of the stop band[19],

$$\frac{\lambda_c}{2} = n_L d_L + n_H d_H \tag{12}$$

For TE-polarization light can now be written as

$$\lambda_c = [(1 - \sin^2\theta_0/n_L{}^2)^{1/2} + (1 - \sin^2\theta_0/n_H{}^2)^{1/2}] \tag{13}$$

λ_c is also a very good approximate for the center of the reflectance band for TM-polarization light. The edge λ_E of the reflection band in given by [19],

$$\lambda_E = \lambda_c\,[1 \mp \Delta g_\Lambda] \tag{14}$$

The longer –wavelength edge of the omnidirectional reflection band is determined by the longer wavelength λ_{Long} TM –reflection edge at 90^oangle of incidence which was called λ_{Long} and shorter – wavelength λ_{short} reflection band edge at 0^o , which was called λ_{short}[19] as shown in Fig. (3). Thus,

$$\lambda_{Long} = (\lambda_c)_{90^o}[1 + (\Delta g)_{90^o}] \tag{15}$$

$$\lambda_{Short} = (\lambda_c)_{90^o}[1 - (\Delta g)_{90^o}] \tag{16}$$

Thus, the normalized omnidirectional band width $\Delta\lambda_{Omni}$ with respect to center wavelength λ_c of the omnidirectional band was defined as [5] ,

$$\frac{\Delta\lambda_{Omni}}{\lambda_c} = 2\,\frac{\lambda_{long}^{TM}(90^o) - \lambda_{short}(0^o)}{\lambda_{long}^{TM}(90^o) + \lambda_{short}(0^o)} \tag{17}$$

Where the omnidirectional bandwidth is given by

$$\Delta\lambda_{Omni} = \lambda_{long}^{TM}(90^o) - \lambda_{short}(0^o) \tag{18}$$

And the center wavelength of omnidirectional band is given by

$$\lambda_c = \frac{1}{2}\,[\lambda_{long}^{TM}(90^o) + \lambda_{short}(0^o)] \tag{19}$$

In terms of n_H and $n_L$the normalized omnidirectional band width is B $=\frac{\Delta\lambda_{Omni}}{\lambda_c}$,

$$B = 2 * \left(\frac{\frac{1}{2}\left[\frac{(n_H^2-1)^{\frac{1}{2}}}{n_H} + \frac{(n_L^2-1)^{\frac{1}{2}}}{n_L}\right]\left[1+\frac{2}{\pi}\sin^{-1}\left(\frac{n_H^2(n_L^2-1)^{\frac{1}{2}} - n_L^2(n_H^2-1)^{\frac{1}{2}}}{n_H^2(n_L^2-1)^{\frac{1}{2}} + n_L^2(n_H^2-1)^{\frac{1}{2}}}\right)\right] - \lambda_o\left[1-\frac{2}{\pi}\sin^{-1}\left(\frac{n_H-n_L}{n_H+n_L}\right)\right]}{\frac{1}{2}\left[\frac{(n_H^2-1)^{\frac{1}{2}}}{n_H} + \frac{(n_L^2-1)^{\frac{1}{2}}}{n_L}\right]\left[1+\frac{2}{\pi}\sin^{-1}\left(\frac{n_H^2(n_L^2-1)^{\frac{1}{2}} - n_L^2(n_H^2-1)^{\frac{1}{2}}}{n_H^2(n_L^2-1)^{\frac{1}{2}} + n_L^2(n_H^2-1)^{\frac{1}{2}}}\right)\right] + \lambda_o\left[1-\frac{2}{\pi}\sin^{-1}\left(\frac{n_H-n_L}{n_H+n_L}\right)\right]} \right) \quad (22)$$

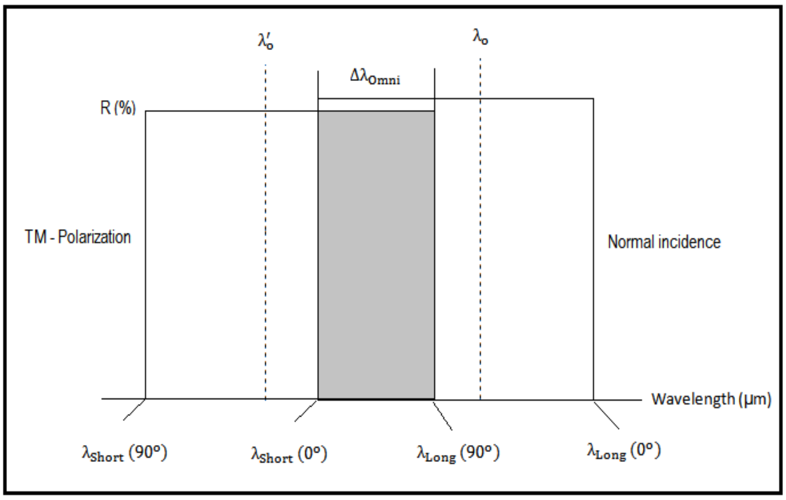

Fig.2:Sketch showing omnidirectional optical performance.

3.Results and Discussion

An algorithm was established using ZEMAX software version 2009 to design " perfect mirror" or , the so called "distributed Bragg reflectors"(DBR) to cover the visible spectral region(0.45-0.85 μm) .The reflectance of dielectric stack was computed using TiO_2 as a high index (n_H=2.58) and SiO_2 (n_L=1.46) as low index material. The optical thickness of high and low materials were *QWOT* at the design wavelength of He-Ne laser line λ_0 =0.6328μm . The effect of increasing the order of periodicity for the selected design :

$$\mathrm{Air[LH]^N glass} \quad \text{and} \quad \mathrm{Air[HL]^N glass}$$

were shown as(R-N) 3D- histogram at normal reflectance in Fig. (4), with result summarized in Table (1).

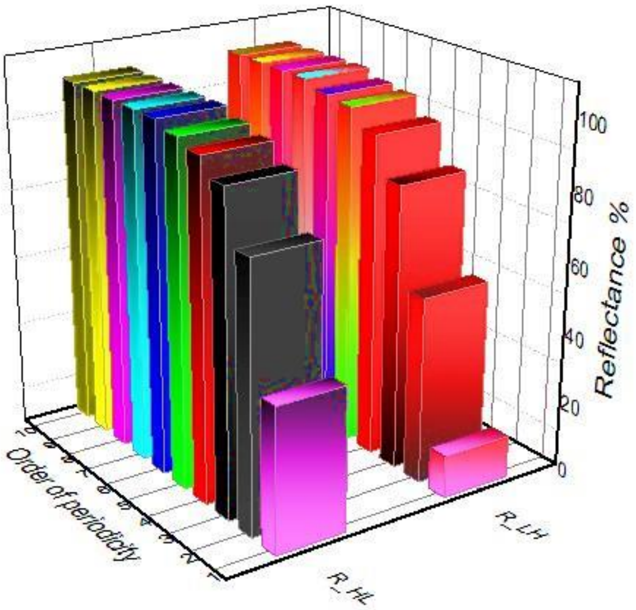

Fig.3: (R-N) 3D- histogram of normal reflectance *vs.* order of periodicity for the two design: $\mathbf{Air[HL]^N glass}$ and $\mathbf{Air[LH]^N glass}$

Table (1): Normal R_{Max} and bandwidth for design Air|(HL)^N |Glass and Air|(LH)^N |Glass at λ_0=0.6328μm .

Design construction	R_{Max} (%)	FWHM (nm)
Air|(HL)^2|Glass	76	____
Air|(LH)^2|Glass	53	____
Air|(HL)^4|Glass	96	328.6
Air|(LH)^4|Glass	92	____
Air|(HL)^6|Glass	100	288.6
Air|(LH)^6|Glass	98	296.8
Air|(HL)^8|Glass	100	270.1
Air|(LH)^8|Glass	100	273.9
Air|(HL)^{10}|Glass	100	258.6
Air|(LH)^{10}|Glass	100	261.8

It is clear that the magnitude of the reflectance increases with the number of layers. The incident angle was considered as variable over the angular range $(0^{O} - 89^{O})$. As the incident angle increases, the admittance η_{TE} increases and that of TM polarization decreases, as shown in Fig. (5).

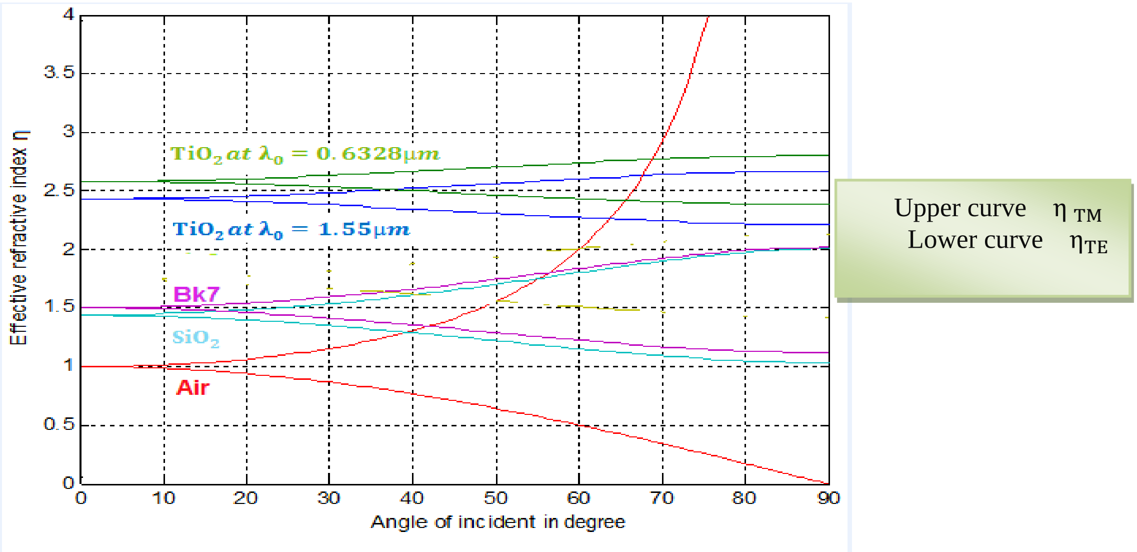

Fig.4: Effective indices η_{TM} and η_{TE} of (TiO2,SiO2 , Air and Bk7glass) *vs.* angle of incident of the light.

So the reflection bandwidth of TE polarization is wider than that at normal incidence, and that of TM polarization is narrower , as shown in Fig.(6). Therefore, at a high incident angle and design wavelength the reflectance of TM-polarized light may be quite low in contrast to the high reflectance of TE polarized light . Fig.(6) represent the conventional photonic band structure for TE and TM polarizations for design Air[LH]^{10} Glass. At 0.6328 μm ,which can be obtained by the projection of $R \approx 1$, the spectra are plotted in terms of wavelength and for incident angle θ_0 . The red region represent the forbidden band and the other colored regions the allowed. The area between the two horizontal lines gives the total omnidirectional reflector (TODR) band. The data for the nearly 100% reflectance is given in Table (2) . For TM polarization the omnidirectional reflection is obtained at 89° angle of incidence and has its range from 0.5258 μm to 0.6028μm for λ_0 =0.6328 μm. Therefore ,omnidirectional reflection for both polarizations(TE and TM) of the considered 1D PC is obtained at 89° angle of incidence and it covers the wavelength region ,λ_H = 0.6028 μm to λ_L= 0.5258 μm , with bandwidth $\Delta\lambda$ =(λ_H+ λ_L) =1.1286nm .Normalized omnidirectional bandwidth is equal to 13.64% at central wavelength λ_C =564.3 nm. Using the design Air $|(LH)^{10}|$ Glass at λ_o=632.8 nm

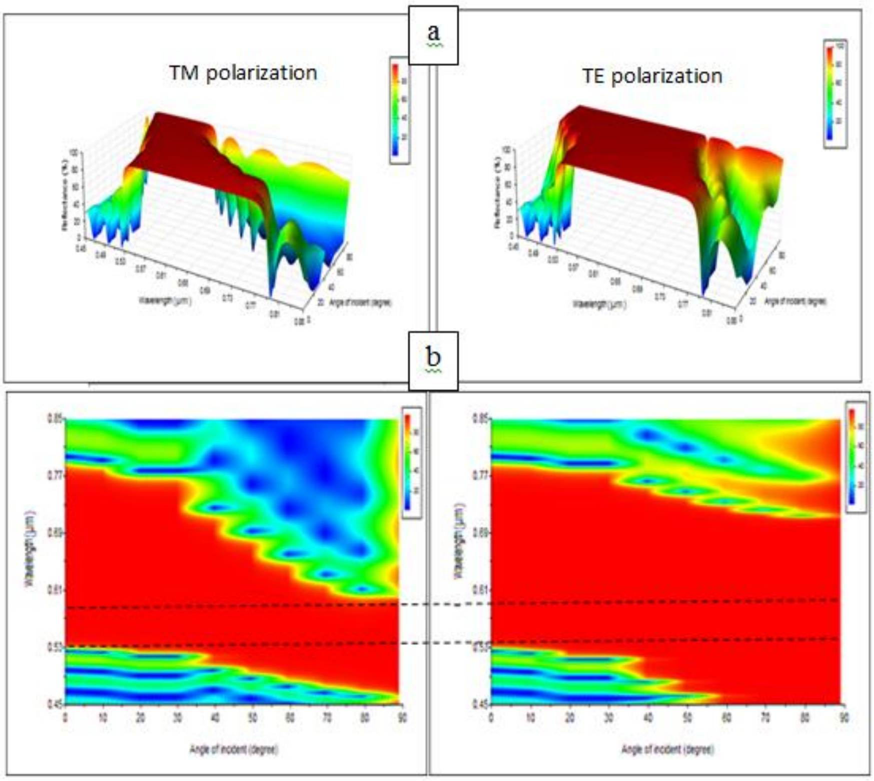

Fig.5: (a) Reflectance spectra of ten-pair TiO_2 / SiO_2 1D PC for TM and TE polarizations , (b) their photonic band structure.

Table(2) Total reflection region and gap width for Air$[LH]^{10}$glass 1D PC at λ_0 =0.6328 μm**.**

Incident angle (degree)	TE polarization		TM polarization	
	Reflection range (μm)	Gap width (nm)	Reflection range (μm)	Gap width (nm)
0	0.5258-0.7975	271.7	0.5258-0.7975	271.7
10	0.5225-0.7942	272.5	0.5225-0.7808	218.8
20	0.5133-0.7858	276.6	0.5183-0.7758	257.5
30	0.4092-0.7758	276.6	0.5108-0.7542	243.4
40	0.4808-0.7617	287.6	0.4975-0.7142	216.7
50	0.4617-0.7493	287.6	0.4867-0.6925	205.8
60	0.4434-0.7349	291.5	0.4755-0.6613	185.8
70	0.4283-0.7226	294.3	0.4679-0.6311	164.1
80	0.4160-0.7142	298.2	0.4613-0.6113	150.0
89	0.4142-0.7123	298.1	0.4613-0.6028	141.5

Conclusion

Zemax software follows by Teraplot as graphic method may be now considered as an alternative good method to evaluate
photonic bandgap directly instead of using Bloch theorem. Thus, the design and evaluation of wideband omnidirectional reflector can be easily evaluated .

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