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BROADENING OF OMNIDIRECTIONAL PHOTONIC BAND GAP IN SI-BASED ONE DIMENSIONAL PHOTONIC CRYSTALS

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Abstract—A simple design of one dimensional gradual stacked photonic crystal (GSPC) structure has been proposed. The proposed structure consists of a periodic array of alternate layers of SiO_2 and Si as the materials of low and high refractive indices respectively. The structure considered here has three stacks of periodic structures with five layers each. The lattice period of successive stack is increased by a certain multiple (say gradual constant, γ) of the lattice period of the just preceding stack. For numerical computation, the transfer matrix method (TMM) has been employed. It is found that such a structure has wider reflection bands in comparison to a conventional dielectric PC structure, and the width of the omni-directional reflection (ODR) bands can be enlarged by increasing the value of the gradual constant. Hence, a GSPC structure can be used as a broadband omnidirectional reflector, and the bandwidth of omni-directional gaps can be tuned to a desired wavelength region by choosing appropriate value of γ.

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1. INTRODUCTION

Since the last two decades, there has been much interest in the study of the physics of photonic crystals (PCs) for understanding their various properties and potential applications. Photonic crystals are structures of materials with periodically modulated dielectric constants. Under some circumstances, photonic crystals can exhibit photonic band gap (PBG) i.e., certain range(s) of wavelengths are forbidden to propagate inside the photonic crystal [1]. By introducing defects in the periodic structure of the PCs, one can attain a very narrow defect mode inside the band gap [2]. This unique feature of the photonic crystal structures dramatically alters the flow of light, and manipulations of photons within the structure can lead to many potential applications in optoelectronics [3–8]. One-dimensional PC structures have many interesting applications such as dielectric reflecting mirrors, low-loss waveguides, optical switches, filters, optical limiters etc. It has been demonstrated theoretically and experimentally that specifically designed one-dimensional PCs exhibit absolute omnidirectional PBGs [9–16].

Recently, gradual multilayer structures have been studied and investigated as a heterogeneous composite material by some researchers [17–19]. It has been found that the physical properties of the graded material are different from those of the homogenous material and conventional composite materials of periodic multilayered structures. In general, graded photonic crystal structures have a variation in either the refractive indices of the alternative layers (keeping the thickness of the constituent layers constant) or a variation in thickness (keeping refractive indices of the constituent layers constant).

In the present communication, we propose a simple design of a broadband reflector using a one-dimensional gradual stacked photonic crystal comprising three stacks of periodic multilayer, each stack having five periods of layers. We increase the lattice period of the successive stacks by a constant rate (which we call the gradual constant, γ). The proposed GSPC structure consists of alternate layers of SiO_2 and Si as materials of low and high refractive indices. In order to calculate the reflection properties, the TMM has been employed. Here, we consider the Si-based material for the proposed structure because it is a good material for the fabrication of photonic devices. Also, it has a large refractive index with excellent mechanical and thermal properties.

2. THEORY

The one-dimensional GSPC structure consists of alternate layers of high and low refractive indices along the x-axis and placed between semi-infinite media of refractive indices n_i (refractive index of the incident medium) and n_s (refractive index of the substrate), as shown in Figure 1.

Applying the TMM, the characteristic matrices for the TE and TM waves have the form [20, 21]

$$M_j = \begin{bmatrix} \cos\beta_j & -\frac{i\sin\beta_j}{q_j} \\ -iq_j\sin\beta_j & \cos\beta_j \end{bmatrix}, \tag{1}$$

where $q_j = n_j \cos\theta_j$, ($j = 1, 2$; for the first and the second layers of the unit cell respectively) for the TE polarization and $q_j = \cos\theta_j/n_j$ for the TM polarization, $\beta_j = (2\pi/\lambda)n_j d_j \cos\theta_j$, θ_j is the ray angle inside the layer of refractive index n_j and λ is the wavelength in the medium of incidence. The total characteristic matrix for the N periods of the structure is given by

$$M = (M_1 \times M_2)^N = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}. \tag{2}$$

The reflection coefficient of the structure for TE and TM polarizations are given by

$$r = \frac{(M_{11} + q_s M_{12})q_i - (M_{21} + q_s M_{22})}{(M_{11} + q_s M_{12})q_i + (M_{21} + q_s M_{22})}, \tag{3}$$

where $q_{i,s} = n_{i,s}\cos\theta_{j,s}$ for TE wave and $q_{i,s} = \cos\theta_{j,s}/n_{i,s}$ for TM wave, where the subscripts i and s correspond to the quantities in the incident medium and substrate respectively. Whereas, the reflectivity of the structure is given by

$$R = |r|^2. \tag{4}$$

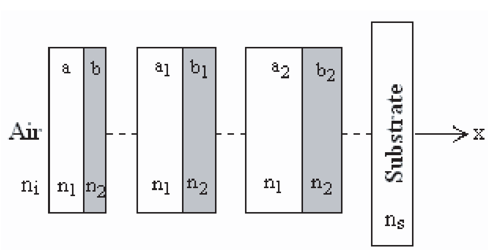

Figure 1. Schematic representation of GSPC structure.

In one-dimensional PCs, there is no absolute photonic band gap (PBG) owing to the two factors. The first is that the edges of the directional PBGs (PBGs at a certain direction) will shift towards the higher frequency side with the increase in incident angle, usually leading to the closure of the overall PBGs. The second is that at the Brewster angle, the TM mode cannot be reflected. However, the absence of an absolute PBG does not mean that there is no omnidirectional reflection. The criterion for the existence of total omnidirectional reflection is that there are no propagating modes that can couple with the incident wave [22]. From Snell's law, we know $n_i \sin\theta_i = n_1 \sin\theta_1$ and $n_1 \sin\theta_1 = n_2 \sin\theta_2$ i.e., $\theta_1 = \sin^{-1}(n_i \sin\theta_i/n_1)$ and $\theta_2 = \sin^{-1}(n_1 \sin\theta_1/n_2)$, where n_1 and n_2 are the refractive indices of the low and high index media respectively, and n_i is the refractive index of the incident medium. The maximum refracted angle is defined as $\theta_2^{\max} = \sin^{-1}(n_i/n_2)$ and Brewster angle is $\theta_B = \tan^{-1}(n_1 \sin\theta/n_2)$. If the maximum refracted angle is smaller than the Brewster's angle then the incident wave from outside cannot couple to Brewster's window which results to total reflection for all incident angles. Thus, the condition for omni-directional reflection without the influence of the Brewster's angle is $\theta_B = \theta_2^{\max}$ [23]. This condition is satisfied by the selected parameters that we have taken for our numerical computations. Hence, in the present analysis there is no influence of Brewster's angle on the omni-directional reflection bands.

3. RESULT AND DISCUSSION

From the computation of Equation (3), the reflection properties of one-dimensional GSPC can be represented graphically. For this purpose, we consider a GSPC structure having the following sequence — air/$(\mathrm{AB})_5$/$(\mathrm{A_1B_1})_5$/$(\mathrm{A_2B_2})_5$/ Substrate(SiO_2). For AB stack, we choose the material of layer A as SiO_2 and the material of layer B as Si having refractive indices 1.5 and 3.7 respectively. Here all the regions are assumed to be linear, homogeneous and non-absorbing. Also, the refractive indices of both the materials are considered to be constant. The thickness of the layers are taken as $a = 283$ nm and $b = 115$ nm according to the quarter wave stack condition $a = \lambda_C/4n_1$ and $b = \lambda_C/4n_2$, where $\lambda_C(= 1700\,\mathrm{nm})$ is the critical wavelength which is the mid-wavelength of the wavelength range considered in our numerical computation. For $\mathrm{A_1B_1}$ stack, we choose the material of layer $\mathrm{A_1}$ as SiO_2 and the material of layer $\mathrm{B_1}$ as Si in which the thicknesses of the layers $\mathrm{A_1}$ and $\mathrm{B_1}$ are taken as $a_1 = \gamma a$ and $b_1 = \gamma b$ respectively, where γ is defined as gradual constant. In a similar way, we choose the material of layer $\mathrm{A_2}$ as SiO_2 and the material of layer $\mathrm{B_2}$

as Si in which the thicknesses of layers A_2 and B_2 are taken as $a_2 = \gamma a_1$ and $b_2 = \gamma b_1$ respectively. The reflectance spectra for conventional PC can be obtained by choosing $\gamma = 1$ in the present structure, whereas for GSPC structures, we consider two cases in which we take the gradual constant $\gamma = 1.1$ and 1.2 respectively.

When $\gamma = 1$, the one-dimensional GSPC structure reduces to the corresponding conventional one-dimensional PC structure. The reflectance spectra of the conventional PC (for both TE and TM polarizations), is shown in Figure 2. The reflectance spectra are plotted as a function of wavelength and for incident angle θ_i. Figure 3, represents the complete photonic band structure in two dimensions which can be obtained by the projections of Figure 2. In Figure 3, the shaded region gives the total omnidirectional reflection band. The data corresponding to nearly 100% reflectance are summarized in Table 1.

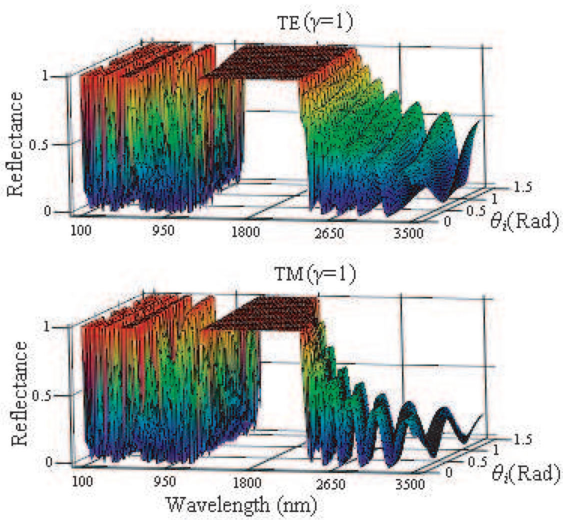

Figure 2. Reflectance spectra of SiO_2/Si one-dimensional PC ($\gamma = 1$) for TE and TM polarizations.

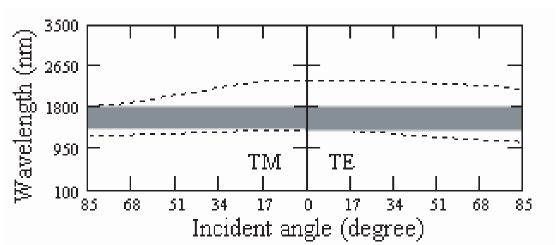

Figure 3. Photonic band structure of SiO_2/Si one-dimensional PC ($\lambda = 1$).

We observe from Table 1 that the TE polarization has its omni-directional reflection range from 1328 nm to 2135 nm and the omni-directional reflection range for the TM polarization from 1328 nm to 1828 nm. Therefore, the total ODR for both TE and TM polarizations when $\gamma = 1$, i.e., for the case of conventional PC, has the bandwidth ($\Delta\lambda = \lambda_H - \lambda_L$) of 500 nm. The upper wavelength edge of the ODR band is $\lambda_H = 1828$ nm and the lower wavelength edge is $\lambda_L = 1328$ nm. Hence, the normalized omni-directional bandwidth is 29.4% of the total wavelength range considered around the critical wavelength $\lambda_C = 1700$ nm.

Table 1. Total reflection region and gap width for SiO_2/Si one-dimensional PC ($\gamma = 1$).

Angle of incidence θ_i (degree)	TE polarization		TM polarization	
	Reflection range (nm)	Gap width (nm)	Reflection range (nm)	Gap width (nm)
0	1328–2366	1038	1328–2366	1038
30	1271–2340	1069	1300–2241	941
60	1150–2268	1118	1242–1971	729
85	1089–2135	1046	1213–1828	615

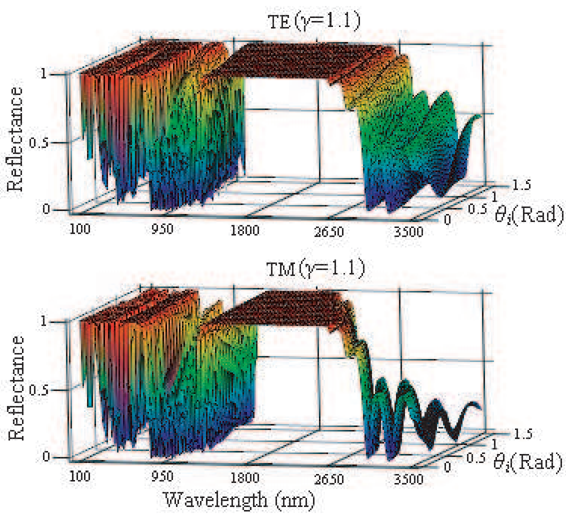

Figure 4. Reflectance spectra of SiO_2/Si one-dimensional GSPC ($\gamma = 1.1$) for TE and TM polarizations.

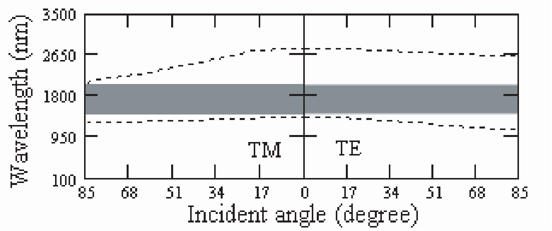

Figure 5. Photonic band structure of SiO_2/Si one-dimensional GSPC ($\gamma = 1.1$).

Table 2. Total reflection region and gap width for SiO_2/Si one-dimensional GSPC ($\gamma = 1.1$).

Angle of incidence θ_i (degree)	TE polarization		TM polarization	
	Reflection range (nm)	Gap width (nm)	Reflection range (nm)	Gap width (nm)
0	1357–2780	1423	1357–2780	1423
30	1301–2744	1443	1317–2602	1285
60	1164–2666	1502	1275–2294	1019
85	1105–2626	1521	1240–2075	835

For $\gamma = 1.1$, the reflectance spectra and photonic band structure of one-dimensional GSPC for both TE and TM polarizations are shown in Figures 4 and 5 respectively and the corresponding ODR data are tabulated in Table 2. We observe from these figures and table that the TE polarization has its ODR range from 1357 nm to 2626 nm and the ODR range for the TM polarization is from 1357 nm to 2075 nm. Therefore, the total ODR (for both TE and TM polarizations) in the case of GSPC structure with $\gamma = 1.1$, has a bandwidth of 718 nm. The upper wavelength edge of ODR band is $\lambda_H = 2075$ nm and the lower wavelength edge of the ODR is $\lambda_L = 1357$ nm. Thus, the normalized omni-directional bandwidth is $\Delta\lambda/\lambda_C = 42.2\%$ of the total wavelength range considered around the critical wavelength $\lambda_C = 1700$ nm. That is the ODR range of one-dimensional GSPC when $\gamma = 1.1$ is 1.44 times of ODR range of conventional PC ($\gamma = 1$).

Also for $\gamma = 1.2$, the reflectance spectra and photonic band structure of GSPC structure for both TE and TM polarizations are shown in Figures 6 and 7 respectively and the corresponding ODR data are tabulated in Table 3. From these Figures and Table, we observe that the TE polarization has its ODR range from 1342 nm to 3103 nm and the ODR range for TM polarization is from 1342 nm to 2376 nm.

Therefore, total ODR (for both TE and TM polarizations) in the case of GSPC structure with $\gamma = 1.2$, has the bandwidth 1034 nm. The upper wavelength edge of ODR band is $\lambda_H = 2376$ nm and the lower wavelength edge of the ODR is $\lambda_L = 1342$ nm. Thus the normalized omni-directional bandwidth is 78.9% of the total wavelength range considered around the critical wavelength $\lambda_C = 1700$ nm. That is, the ODR range of GSPC in the case when $\gamma = 1.2$, is 1.44 times of ODR range for $\gamma = 1.1$ and 2 times of ODR range of $\gamma = 1$.

Finally, by increasing the value of gradual constant γ in steps 0.01, the variation in ODR range with gradual constant (γ) is plotted as shown in Figure 8. Here, the gap between two dotted lines shows the ODR range for a particular value of γ.

Table 3. Total reflection region and gap width for SiO_2/Si one-dimensional GSPC ($\gamma = 1.2$).

Angle of incidence θ_i (degree)	TE polarization		TM polarization	
	Reflection range (nm)	Gap width (nm)	Reflection range (nm)	Gap width(nm)
0	1342–3299	1957	1342–3299	1957
30	1287–3252	1965	1315–3172	1857
60	1164–3153	1989	1243–2547	1304
85	1111–3103	1990	1234–2376	1142

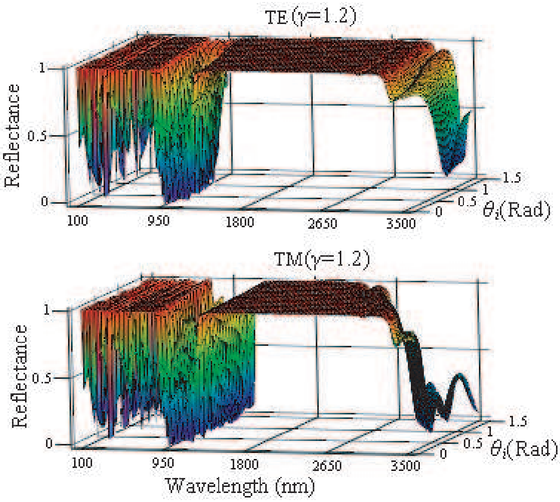

Figure 6. Reflectance spectra of SiO_2/Si one-dimensional GSPC ($\gamma = 1.2$) for TE and TM polarizations.

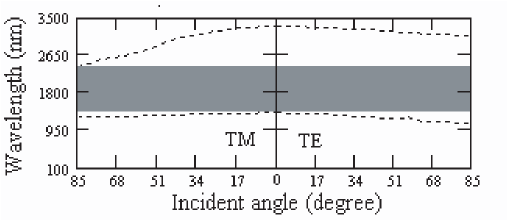

Figure 7. Photonic band structure of SiO_2/Si one-dimensional GSPC ($\gamma = 1.2$).

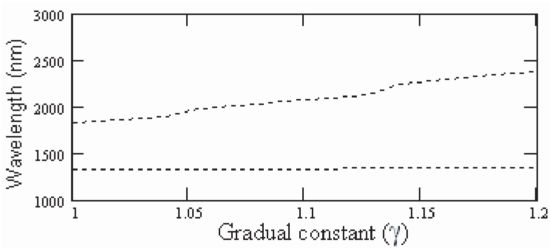

Figure 8. Variation of ODR range with gradual constant.

From Figure 8, it is clearly observed that the ODR range for $\gamma = 1.2$ is just double of ODR range for $\gamma = 1$. So, by choosing appropriate values of controlling parameters we can tune the ODR range. The ODR range for GSPC can be enhanced by increasing the value of γ. It is observed that in a GSPC structure, the ODR band gets enhanced without increasing the number of layers of the structure. It is found that the ODR range for GSPC structure is generally more than the ODR range of conventional PC. Also, it is more than the ODR bandwidth of simple graded PC structure [24].

4. CONCLUSION

To summarize, we have investigated theoretically the ODR range of one-dimensional GSPC structure. It is found that the ODR range of GSPC structure can be enhanced by increasing the value of gradual constant and that the ODR range for one-dimensional GSPC structure is more than that of conventional PC and simple graded structure. Hence, a one-dimensional GSPC structure can be used as a broadband optical reflector, and the range of reflection can be tuned to a desired wavelength region by varying the value of gradual constant and also by choosing proper thickness of the period (d) of first stack and relative thicknesses of individual layers of the following stacks. These types of optical reflectors are compact in size and may have potential applications in the field of optical technology and optoelectronics.

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