THERMAL TUNING OF OMNI-DIRECTIONAL REFLECTION BAND IN SI-BASED 1D PHOTONIC CRYSTAL

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\textbf{ABSTRACT}

The temperature dependence of the omni-directional reflection (ODR) band in a one-dimensional photonic crystal is proposed simultaneously considering thermal expansion effect and thermo-optic effect. The structure proposed in this study consists of a periodic arrangement of alternate layers of SiO\textsubscript{2} as the material of low refractive index and Si as the material of high refractive index. As the refractive index and thickness of both materials used in this study are modulated by temperature, the ODR band can be tuned as a function of temperature. With the increase of temperature, it is noted that the ODR band shifts towards the longer wavelength region. Also, the ODR band broadens slightly. The ODR band can be tuned by variation in the operating temperature of the structure.

\textbf{KEYWORDS}

Omnidirectional reflection, Photonic crystal, Thermal expansion, Transfer matrix method

1. INTRODUCTION

Recently, the study of various properties and potential applications of photonic crystals (PCs) have become an area of intense research. Photonic crystals are structures of materials generally with periodically modulated dielectric constants. Under some conditions, photonic crystals can exhibit complete photonic band gaps (PBGs) i.e. some range(s) of the wavelengths of incident wave that are reflected by the photonic crystal structure [1]. By introducing defect(s) in the periodic structure of the PCs, one can obtain localized defect mode inside the forbidden band gap [2]. This property of the photonic crystals guides the flow of light and manipulates the propagation of photons within the PCs. This property can be used in many interesting applications of optoelectronics [3-7]. One dimensional PC structures have many applications such as low-loss optical waveguides, dielectric reflecting mirrors, optical switches, optical limiters, optical filters etc. It has been demonstrated experimentally and theoretically that one-dimensional PCs have complete omni-directional PBGs [8-13].

An omni-directional reflector is a mirror having 100% reflectivity at any angle of incidence for TE polarized as well as TM polarized waves. In 1998, Fink et al. reported that one-dimensional dielectric lattice displays total omni-directional reflection for incident light under certain conditions [14, 15]. They constructed a stack of nine alternate layers of polystyrene/tellurium having a thickness of the order of ~ m and demonstrated omni-directional reflection over the wavelength range from 10-15 m. Gallas et al. [16] reported the annealing effect in the Si/SiO\textsubscript{2}
PBG based omni-directional reflectors. Wang et al. [17] theoretically showed that overlapping two photonic crystals could enlarge the range of total omni-directional reflection.

Mostly, photonic crystals have been made from III–V semiconductors. While the thermal effects of these semiconductors are changed various optical properties of PCs. Previous reports on omni-directional reflection were without taking the thermal effect. In this article, the design of an omni-directional reflector using a one-dimensional photonic crystal has been proposed considering the temperature modulation of thickness and refractive index on each alternate layer. The effect of temperature on thickness is called thermal expansion effect and effect of temperature on refractive index is called thermal-optical effect. The structure proposed in this study consists of a periodic arrangement of alternate layers of SiO\(_2\) as the material of low refractive index and Si as the material of high refractive index. As the refractive index and thickness of both materials used in this study are modulated by temperature, the ODR band can be tuned as a function of temperature. With the increase of temperature, it is noted that the ODR band shifts towards the longer wavelength region. Many researchers have been worked on thermal tuning of photonic band gaps and defect modes [18–24]. But to the best of our knowledge no other thermal tuning ODR based theoretical/or experimental research has been worked out.

2. THEORETICAL MODEL

We consider a multi-layered structure [air/(n\(_1\)n\(_2\))\(^{10}\)/air] which consists of alternate layers of materials of high and low refractive indices along the x- axis, as shown in Figure 1.

![Graphical representation of the proposed Structure](image)

By employing the transfer matrix method (TMM), the matrices for both polarized waves (TE and TM) for a bilayer system of such a structure is given by [25, 26]

\[
A_j = \begin{bmatrix}
\cos \phi & \frac{-i \sin \phi}{p_j} \\
\frac{-ip_j \sin \phi}{p_j} & \cos \phi
\end{bmatrix}
\]

(1)

where \(p_j=n_j \cos \theta_j\) ( \(j=1,2\) ) for the TE mode of polarization and \(p=\cos \theta/n_j\) for the TM mode of polarization, \(\phi=(2\pi/\lambda) n_j d \cos \theta, \theta\) is the angle of incidence of the propagated wave inside the layer with refractive index \(n_j\) and \(\lambda\) is the wavelength of the propagated wave in the medium of incidence (air). The characteristics matrix for the proposed structure having N unit cells is given by

\[
A = (A_j)^N = \begin{bmatrix}
A_{11} & A_{12} \\
A_{21} & A_{22}
\end{bmatrix}
\]

(2)
The reflection coefficient of the proposed structure for TE and TM polarized waves are given by

\[ r = \frac{(A_{11} + p_{f}A_{12})p_{i} - (A_{21} + p_{f}A_{22})}{(A_{11} + p_{f}A_{12})p_{i} + (A_{21} + p_{f}A_{22})} \]  

(3)

where \( p_{i} = n_{i} \cos \theta_{i} \) for TE polarized wave and \( p_{i} = (\cos \theta_{i})/ n_{i} \) for TM polarized wave, where the subscripts \( i \) and \( f \) correspond to the medium of incidence and the medium of emergence respectively. The reflectivity of the proposed structure can be given as

\[ R = |r|^{2} \]  

(4)

There is no complete photonic band gaps (PBG) in one-dimensional PCs due to the two factors. The first factor is that the edges of the directional PBGs (PBGs at a certain region) will shift towards the longer frequency side with the increase in angle of incidence, usually leading to the disappearance of the overall PBGs. The second factor is the Brewster angle; at which the TM polarized wave cannot be reflected. However, the absence of a complete PBG does not mean that there is no omni-directional reflection. The criterion for the existence of total omni-directional reflection is that there are no waves propagate through the PC for both modes of polarization \([10,12,16]\). 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. \( \theta_{1} = \sin^{-1}(n_{1} \sin \theta_{i} / n_{i}) \) and \( \theta_{2} = \sin^{-1}(n_{1} \sin \theta_{i} / n_{2}) \), where \( n_{1} \) and \( n_{2} \) are the refractive indices of the low and high refractive index mediums respectively, and \( n_{i} \) is the refractive index of the incident medium. The maximum refracted angle is defined as \( \theta_{2}^{\text{max}} = \sin^{-1}(n_{1} / n_{2}) \) and the Brewster angle is given by \( \theta_{B} = \tan^{-1}(n_{1} \sin \theta_{i} / n_{2}) \). If the Brewster’s angle is greater than the maximum angle of refraction, then the propagated wave cannot couple to Brewster’s window which is the condition of owing total reflection for all modes of polarization and angles of incidence. Thus, Brewster’s angle must be equal to maximum angle of refraction for omni-directional reflection i.e. \( \theta_{B} = \theta_{2}^{\text{max}} \)[10,12,27]. This condition must be satisfied by parameters used in our numerical computations.

3. RESULTS AND DISCUSSION

From the computation of Equation (4), the reflection properties of one-dimensional photonic crystals simultaneously considering thermal expansion effect and thermal-optic effect can be represented graphically. For this purpose, we consider the PC structure having \( n_{1} \) and \( n_{2} \) as refractive indices of SiO\(_{2}\) and Si respectively \((n_{1} < n_{2})\). Si is the good candidate for the photonic crystals especially in infrared region because of its very low absorption in this region. Crystalline Si has been taken in this study. The refractive indices are taken considering thermo-optic effect in the following manner

\[ n_{1}(T) = n_{1}(1+\gamma_{1} \ T) \text{ and } n_{2}(T) = n_{2}(1+\gamma_{2} \ T) \]  

(5)

where \( n_{1} = 1.46 \), \( n_{2} = 3.4 \) and \( \gamma_{1}, \gamma_{2} \) are called the thermo-optic coefficients for the SiO\(_{2}\) and Si materials respectively. The values of these coefficients are taken as \( \gamma_{1} = 1.86 \times 10^{-7} / \text{C} \) and \( \gamma_{2} = 6.8 \times 10^{-6} / \text{C} \)[28].

The thickness of each layer is taken considering the effect of thermal expansion of each layer in the following manner

\[ a = a(1+\alpha_{1} \ T) \text{ and } b = b(1+ \alpha_{2} \ T) \]  

(6)

where \( \alpha_{1}, \alpha_{2} \) are called the thermal expansion coefficients for the SiO\(_{2}\) and Si materials respectively. The values of these coefficients are taken as \( \alpha_{1} = 2.6 \times 10^{6} / \text{C} \) and \( \alpha_{2} = 0.5 \times 10^{6} / \text{C} \)[28].
The thickness of the layers of proposed structure are taken as $a=300\text{nm}$ and $b=129\text{nm}$ according to the quarter wave stack condition $a=\lambda_c/4n_1$ and $b=\lambda_c/4n_2$, with the critical wavelength, $\lambda_c=1750\text{nm}$. The critical wavelength is the mid wavelength of the spectrum considered in this computation. The ODR band is found in the vicinity of this critical wavelength. So the optical paths for the incident radiation of each material are equal. The reflectance spectra of the proposed PC (for both TE and TM polarizations) at 30°C, is shown in Figure 2. The reflectance spectra are plotted in terms of wavelength and for incident angle $\theta_i$. Figure 3, represents the complete photonic band structure shown as a function of the angle incidence, which can be obtained by the projections of Figures 2(a) and 2(b). In Figure 3, the shaded region gives the total omnidirectional reflection band. The data corresponding to nearly 100% reflectance is summarized in Table 1.
TABLE 1: TE, TM AND ODR BAND GAP AT ROOM TEMPERATURE T=30°C

<table>
<thead>
<tr>
<th>Mode</th>
<th>Upper (nm)</th>
<th>Lower (nm)</th>
<th>Band Gap (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM</td>
<td>1815.6</td>
<td>1404.2</td>
<td>411.4</td>
</tr>
<tr>
<td>TE</td>
<td>2243.0</td>
<td>1404.2</td>
<td>838.8</td>
</tr>
<tr>
<td>Complete ODR</td>
<td>1815.6</td>
<td>1404.2</td>
<td>411.4</td>
</tr>
</tbody>
</table>

TABLE 2: ODR BAND WITH THE TEMPERATURE

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Upper Edge of ODR Band (nm)</th>
<th>Lower Edge of ODR Band (nm)</th>
<th>Mid-Gap of ODR Band (nm)</th>
<th>ODR Band Gap (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1815.9</td>
<td>1404.4</td>
<td>1610.15</td>
<td>411.5</td>
</tr>
<tr>
<td>100</td>
<td>1816.7</td>
<td>1404.9</td>
<td>1610.80</td>
<td>411.8</td>
</tr>
<tr>
<td>150</td>
<td>1817.5</td>
<td>1405.4</td>
<td>1611.45</td>
<td>412.1</td>
</tr>
<tr>
<td>200</td>
<td>1818.3</td>
<td>1405.8</td>
<td>1612.05</td>
<td>412.5</td>
</tr>
<tr>
<td>250</td>
<td>1819.1</td>
<td>1406.3</td>
<td>1612.70</td>
<td>412.8</td>
</tr>
<tr>
<td>300</td>
<td>1819.9</td>
<td>1406.8</td>
<td>1613.35</td>
<td>413.1</td>
</tr>
<tr>
<td>350</td>
<td>1820.7</td>
<td>1407.3</td>
<td>1614.00</td>
<td>413.4</td>
</tr>
<tr>
<td>400</td>
<td>1821.5</td>
<td>1407.8</td>
<td>1614.65</td>
<td>413.7</td>
</tr>
<tr>
<td>450</td>
<td>1822.3</td>
<td>1408.3</td>
<td>1615.30</td>
<td>414.0</td>
</tr>
<tr>
<td>500</td>
<td>1823.1</td>
<td>1408.8</td>
<td>1615.95</td>
<td>414.3</td>
</tr>
</tbody>
</table>

Figure 3: Complete ODR Bandgap for both TE & TM mode of polarization and whole angle of incidence at room temperature T=30°C

From Table 1 it is observed that the TE polarized wave has its 100% reflection range from 1404.2nm to 1815.6nm and the 100% reflection range for the TM polarized wave is from 1404.2nm to 2243.0nm. Therefore, the range for which both the polarizations (TE and TM) exhibit 100% reflection i.e. omni-directional reflection (ODR) has the bandwidth ($\Delta\lambda=\lambda_H-\lambda_L$) of 411.4nm. The upper edge of the complete band gap i.e. ODR band is $\lambda_H=1815.6$nm and the lower wavelength edge is $\lambda_L=1415.2$nm. Our aim is to tune the ODR band due to the variation of
temperature. The variations of ODR band gap with temperature (30-500 °C) are shown in table 2. Table 2 indicate that with the increase of temperature the ODR range increases slightly. The average change in the ODR band is 0.006nm/°C. As we increase the temperature, the middle of the ODR band shifts toward the longer wavelength region. This is approximately 0.013/°C, which is just double of the broadening of ODR bands. This shifting behavior of ODR bands can be explained by using the phase equation \( \phi_j = (2\pi/\lambda)n_j(T)d_j(T)\cos\theta \), where \( j=1,2 \). According to this phase equation, as \( n_j(T) \) and \( d_j(T) \) increase with temperature, the wavelength must increase accordingly to keep the phase \( \phi_j \) unchanged. Correspondingly, the value of wavelength must increase.

The variation of the middle of the ODR band with temperature is shown in Figure 4. From this figure, it is clear that the change in the middle of the ODR band is linear approximately. Also, the variation of the band width of ODR band with temperature is shown in Figure 5. This Figure shows that the ODR band width also change linearly with temperature. So, we can tune the ODR band width as well as middle of the ODR band to the desired wavelength region by choosing the appropriate temperature of the medium.

![Figure 4: Variation in Mid-gap with Temperature](image)

![Figure 5: Variation in Bandgap with Temperature](image)

The variation of the middle of the ODR band with temperature is shown in Figure 4. From this figure, it is clear that the change in the middle of the ODR band is linear approximately. Also, the variation of the band width of ODR band with temperature is shown in Figure 5. This Figure shows that the ODR band width also change linearly with temperature. So, we can tune the ODR band width as well as middle of the ODR band to the desired wavelength region by choosing the appropriate temperature of the medium.
3. CONCLUSIONS

To summarize, we have investigated theoretically the ODR range of PC structure considering simultaneously thermo-optic and thermal expansion effects. It is observed that the ODR range of proposed photonic crystal structure can be tuned by increasing the operating temperature. These types of optical reflectors are compact comparatively and may have many useful applications in photonics and optoelectronics such as optical sensors, optical filters, etc.

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