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Tuning of Reflection Band as a function of Temperature in One Dimensional Photonic Crystal

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Abstract

The thermal expansion effect and the thermo-optic effect can be employed for controlling the photonic band gaps in photonic crystals. The temperature dependence of the omni-directional reflection (ODR) band in a one-dimensional photonic crystal is proposed simultaneously considering both effects. SiO_2 and Si are used as the high refractive index material and low refractive index materials in the present study. The refractive indices of both materials depend on the temperature of the structure. This property can be employed to tuning the reflection bands of the structure. Transfer matrix method is applied for computing the reflection spectra.

Keywords: Photonic Crystal, Thermal Expansion Effect, Thermo-Optic Effect, Transfer Matrix Method Etc.

Introduction

Photonic Band Gap materials are materials which have band gap(s) due to the periodicity in the refractive indices. Photonic band gap materials are also known as Photonic Crystals. Photonic crystals can be fabricated creating periodicity in one, two, or three dimensions. The band gaps in photonic crystals are represented by the stopped energy range where wave behaving photons cannot be transmitted through the structure. An omni-directional reflector (ODR) is a structure having cent percent reflectivity for all angles of incidence as well as for both TE and TM polarized electromagnetic waves. This study is demonstrated theoretically that ODR bands can be controlled remarkably by temperature of the structure.

Aim of the Study

Photonic crystals are attractive artificial optical materials used for controlling and manipulating light flow. This study is more physically realistic because thermo-optic as well as thermo-expansion effect are considered simultaneously in computing the band gaps. Tuning of ODR band are useful in the devices where cent percent reflection are required e.g. spaceship etc.

Review of Literature

Recently, the study of various properties and potential applications in many devices based on photonic crystals (PCs) has become an area of intense research. Photonic crystals are structures of multiple materials modulated in periodic fashion with their dielectric constants. Under some conditions, photonic crystals can exhibit band gaps also called photonic band gaps (PBGs) i.e. certain range(s) of optical wavelengths or frequencies that are forbidden to propagate within the materials [1]. By inserting any more layer(s) or removing any layer from the geometry in the periodicity defect can be introduced in the structure of the PCs. These defects can create the very narrow defect mode inside the band gap[2]. Due to this unique feature of the photonic crystals many potential applications are possible. The defect mode(s) in the structures alters dramatically the flow of photon within the structure and can lead to many potential applications as optoelectronic devices [3-7]. There are many interesting applications such as dielectric reflecting mirrors, low-loss waveguides, optical switches, filters, and optical limiters etc using one-dimensional PC structures. Omni-directional reflection is one of the interesting properties of PCs and it has been demonstrated theoretically and experimentally in one-dimensional PCs [8-12].

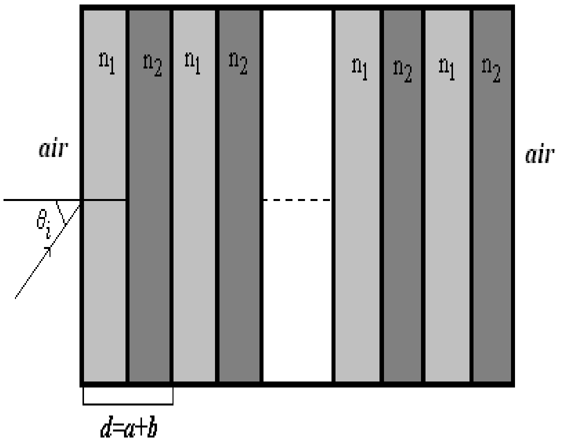
An omni-directional reflector is a mirror having cent percent reflection (or zero percent transmission) at all angle of incidence for both TE and TM polarized EM waves. In 1998, Fink et al. found that one-dimensional dielectric modulated materials shows total omni-directional reflection for incident radiation under certain conditions [13, 14]. They modulated a stack of nine alternate layers of polystyrene and tellurium with the thickness of the order of ~μm and demonstrated omni-directional reflection over the wavelength range from 10-15 μm. Gallas et al. [15] reported the annealing effect in the Si/SiO_2 based PC which leads to the omni-directional reflection. Wang et al. [16] theoretically showed that it is possible to enlarge the omni-directional reflection range by overlapping two/three photonic crystals.

Mostly, photonic crystals have been made using the materials of III–V group semiconductors. The thermal effects of these semiconductors can also change the optical properties of PCs. All previous reports on omni-directional reflector were without considering the thermal effect of these semiconductors. In this communication, a simple design of an omni-directional reflector using semiconductor based one-dimensional photonic crystal has been proposed by considering the temperature dependent parameters i.e. thickness and index of refraction on each constituent layer. In the proposed structure SiO_2 and Si have been chosen as the materials of low and high refractive indices. As the index of refraction and thickness of each material are depended on temperature, the ODR band can controlled as a function of temperature.

Theoretical Model

Consider a multilayer structure $[air/(n_1n_2)^{10}/air]$ is consisting alternate layers of materials of low (n_1) and high (n_2) refractive indices along the x- axis. The schematic is shown in Figure 1.

Figure 1: Schematic Diagram of One-Dimensional Proposed Structure



Applying the transfer matrix method (TMM) for computation, the characteristic matrices of the structure for the TE and TM polarized waves is given by [24, 25]

$$M_j = \begin{bmatrix} \cos\delta_j & -\dfrac{i.\sin\delta_j}{q_j} \\ -iq_j\sin\delta_j & \cos\delta_j \end{bmatrix} \qquad (1)$$

where $q_j=n_j\cos\theta_j$, (j=1,2) for the TE wave and $q_j=\cos\theta_j/n_j$ for the TM wave, $\delta_j=(2\pi/\lambda)n_jd_j\cos\theta_j$, θ_j is the angle of incidence, n_j is the refractive index and λ is the wavelength in the medium of incidence (air). The above characteristics matrix for the N unit cells will be in the form given below

$$M=(M_j)^N=\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \qquad (2)$$

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

$$r=\frac{(M_{11}+q_fM_{12})q_i-(M_{21}+q_fM_{22})}{(M_{11}+q_fM_{12})q_i+(M_{21}+q_fM_{22})} \qquad (3)$$

where $q_{i,f}=n_{i,f}\cos\theta_{j,f}$ for TE wave and $q_{i,f}=(\cos\theta_{j,f})/n_{i,f}$ for TM wave, where the subscripts i and f stands for the medium of incidence and the medium of emergence respectively. Whereas, the reflectivity of the structure can be computed as

$$R=|r|^2 \qquad (4)$$

There are two factors to exist photonic band gap(s) in one-dimensional PCs. According to the first factor the band edges shifts towards the higher frequency side with increase in angle of incidence. The second factor is that at the Brewster angle, the TM polarized wave cannot be reflected. In 2001 Gallas et.al studied on omni-directional reflection (ODR) and defined the criterion for ODR bands. The criterion for the existence of total omni-directional reflection is that there are no propagating modes that can couple with the incident wave [15]. 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 the Brewster angle is given by $\theta_B=\tan^{-1}(n_1\sin\theta/n_2)$. For obtaining ODR bands it is mandatory that the Brewster's angle is greater than angle of incidence which results to total reflection for all incident angles and for both modes of polarizations. Thus, the mandatory condition for omni-directional reflection without the influence of the Brewster's angle is $\theta_B=\theta_2^{\max}$ [26]. This condition can be satisfied by selecting appropriate computing parameters. Hence, in the present analysis the computing parameters chosen in such a way that there is no influence of Brewster's angle on the omni-directional reflection bands.

Results and Discussion

The reflection properties of one-dimensional photonic crystals can be computed graphically using Transfer Matrix Method. In this section, Equation (4) is used to calculate the reflection spectra of proposed structure. In the present study thermal expansion effect (expansion in thickness of layers) and thermal-optic effect (variation in refractive indices) are considered simultaneously. For the structure as shown in Figure 1, the materials are chosen as SiO_2 and Si for refractive indices n_1 and n_2 respectively. Crystalline Si and SiO_2 have been taken for this study because these two materials are widely used in

Photonics especially in infrared region because of their very low absorption in this region. The refractive indices depend on temperature in the following manner

$$n_1(T)= n_1(1+\alpha_1\Delta T) \text{ and } n_2(T)= n_2(1+ \alpha_2\Delta T) \quad (5)$$

Where n_1=1.5, n_2=3.7 (refractive indices in infrared region) and α_1, α_2 are called the thermo-optic coefficients for the SiO$_2$ and Si materials respectively. The values of these coefficients are chosen as $\alpha_1=1.86 \times 10^{-4}$ /°C and $\alpha_2=6.8 \times 10^{-6}$ /°C [27]. The refractive index of SiO$_2$ layers are increase more per degree of temperature in comparison of Si layers. So refractive index contrast is decreased with temperature. The property of the proposed structure can be employed to tune the ODR bands.

The thickness of each layer is taken considering the effect of temperature on thickness of both layers as follows

$$a=a(1+\beta_1\Delta T) \text{ and } b=b(1+ \beta_2\Delta T) \quad (6)$$

Where β_1, β_2 are called the thermal expansion coefficients for the SiO$_2$ and Si layers respectively. The values of these coefficients are chosen as $\beta_1=2.6 \times 10^{-6}$ /°C and $\beta_2=0.5 \times 10^{-6}$ /°C [27]. The thickness of the layers are taken as a:b=3:1. The thickness and thermal expansion coefficient of SiO$_2$ layers are greater than the thickness of Si layers. These properties are also useful in controlling the ODR band. The reflectance spectra of the proposed structure for chosen parameters at room temperature, is shown in Figure 2. The reflectance spectra are projected as the function of wavelength and angle of incidence. Figure 2, represents the complete photonic band gap for both TE and TM mode of polarization. In Figure 2, the common shaded region for both polarizations gives the total omni-directional reflection band. Table 1 is representing the almost cent percent reflection wavelength ranges and corresponding ODR range too.

Figure 2: Absolute ODR Gap of Proposed Structure for both TE & TM Polarized Waves at Room Temperature

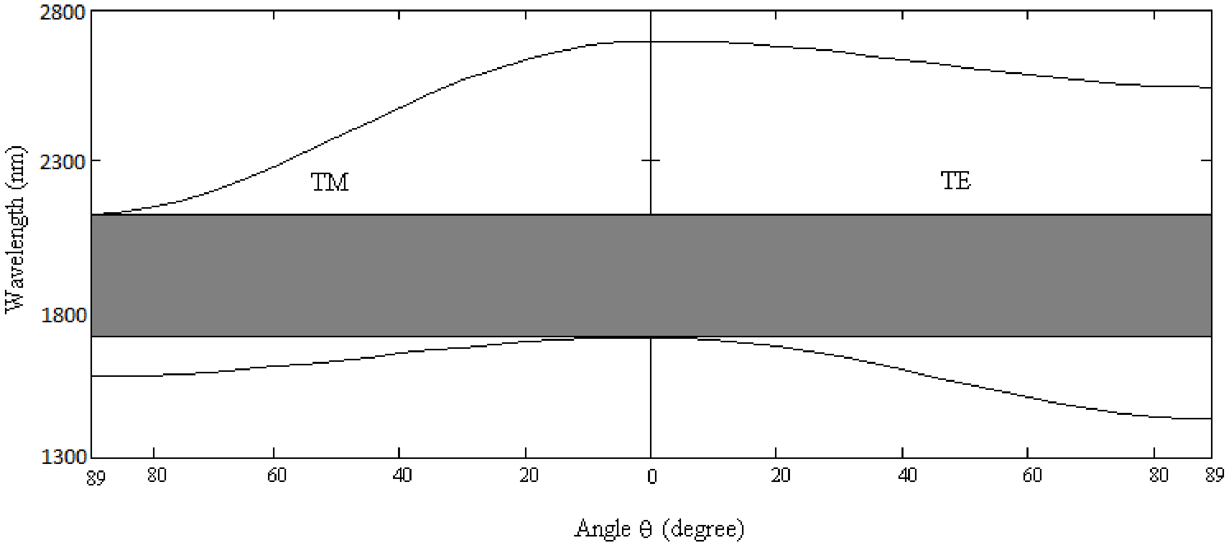


Table 1: TE, TM and ODR Gap of Proposed Structure at Room Temperature

Mode	Upper (nm)	Lower (nm)	Band Gap (nm)
TM	2115.6	1714.4	401.2
TE	2548.4	1714.4	834.0
Complete ODR	2115.6	1714.4	401.2

It is observed from Table 1 that at normal incidence both TE and TM modes of polarizations are identical i.e. having the same band edges. The TE polarized wave has its ODR band range from 1714.4nm to 2548.4nm whereas the ODR range for the TM polarized wave is from 1714.4nm to 2115.6nm. Therefore, the wavelength range for which both the TE and TM modes of polarizations exhibit cent percent reflection i.e. ODR band has the bandwidth of 401.2nm. This ODR band can be tuned as the function of the temperature of the structure. In the present communication the main aim of study is to tune the ODR band as the function of temperature. The variation of ODR band at room temperature from 0 °C to 600 °C is depicted in Figure 3.

Figure 3: Variation in Bandgap with Temperature from 0 °C to 600 °C

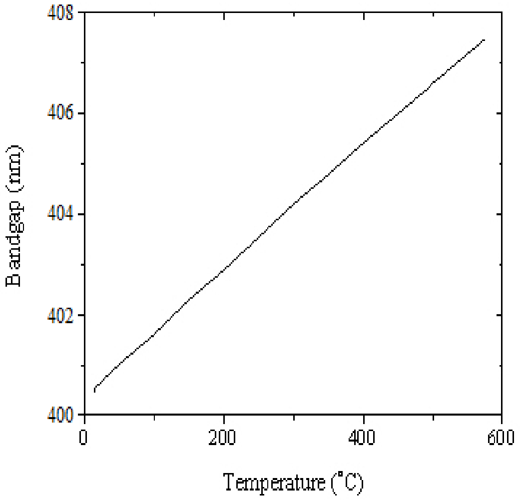


Figure 3 shows that the ODR band gap increases linearly with the rise in temperature. Also the mid-point of the ODR band gap shifts toward the longer wavelength side for higher temperature. This shift in ODR band is due to the temperature dependent refractive indices and thickness of both media. This behavior can be interpreted by phase equation $\delta_j=(2\pi/\lambda)n_j(T)d_j(T)\cos\theta_j$ where j=1,2. As $n_j(T)$ and $d_j(T)$ increase with temperature, the ODR band shifts towards longer wavelength to keep the phase δ_j constant. This Figure also demonstrate that the ODR band can be tuned as the function of temperature because its changes with temperature in a linear manner. So the ODR band can be shifted towards shorter or longer wavelength by selecting desired temperature.

Conclusions

To summarize, it is investigated theoretically that the ODR band in one-dimensional PCs can be controlled as the function of temperature. Such types of optical reflectors/mirrors are very compact in size and may have many useful applications in photonics as photonic sensors, filters and in many devices where temperature is an important parameter.

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