Photonic Band Gaps as the function of temperature in One-Dimensional Photonic Crystal

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Abstract

Photonic band gap as the function of temperature in one-dimensionalphotonic crystalconsisting alternate layers of Si and air has been presented. In this study, semiconductor/dielectric multilayer system has been considered because of the high melting point of semiconductor materials. The refractive index of Si layers is taken temperature dependent as well as wavelength dependent. So the photonic band gap of the proposed structure can be controlled from the temperature of the structure. The propagation characteristic of the proposed one-dimensional structure isanalyzed by transfer matrix method.

Keywords: Photonic Bandgap, Multilayer, Transfer Matrix Method Etc.

Introduction

A photonic crystal is a periodic optical nanostructure that affects the motion of photons in periodic array as much as ionic lattices affect electrons in solids.Photonic crystals can be fabricated for one, two, or three dimensions depending the periodicity of the structure .The band gap in photonic crystals represents the forbidden energy range where wave behaving photons cannot be transmitted (or cent percent reflected) through the material. This study is demonstrated theoretically that such photonic band gaps can be controlled remarkably by temperature of the structure.

Aim of the Study

Photonic crystals are attractive optical materials for controlling and manipulating electromagnetic flow through it. One dimensional photonic crystals are having multipurpose applications in the form of thin-film optics, with applications from low and high reflection coatings on lenses and mirrors to color changing paints and inks. This idea also can be employed in temperature sensing devices, narrow band optical filters, wavelength division de-multiplexers, tunable omni-directional reflectors and in many electro-optical systems.

Review of Literature

The artificial structures with periodically modulated dielectric constants have been attracting a great deal of interest among the researchers after the works of E. Yablonovitch[1] and S. John[2].The pioneering research on the optical properties of photonic crystals which are photonic crystals that exhibit electromagnetic forbidden bands or photonic band gaps (PBGs) have received considerable attention over last four decades.This idea can be exploited in the study of fundamental physical properties as well as for the potential applications in many optoelectronic devices[3-13]. It was observed that periodic modulation of the dielectric constants modifies significantly the electromagnetic properties of the incident radiation. The electromagnetic transmissions of the EM wave in such structures are characterized by the presence of allowed and forbidden photonic bands in the same way as electronic band structure of periodic potentials. For this reason, such a new type of artificially designed optical material with periodic dielectric modulation is known as photonic band gap (PBG) material [14]. Fundamental optical properties like band structure, transmittance, reflectance, group velocity, etc. can be controlled effectively using such periodic dielectric function [5,6].

A 1D PC structure has many interesting applications such as dielectric low-loss waveguides, reflecting mirrors, optical filters, optical sensors, optical switches, optical limiters etc. It has also been demonstrated theoretically as well as experimentally that 1DPCs have absolute band gaps i.e. omni-directional PBGs [15-19].

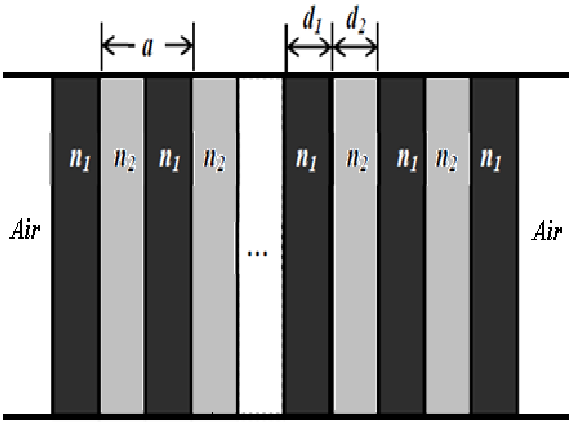
In addition to the existence of wide photonic band gaps in PCs, the feature of a tunability of band gaps attracts the attention of researchers in recent years. PBGs can be tuned by means of some external agents e.g. temperature, pressure, electric/magnetic field etc. For instance, bandgaps can be shifted by the operating temperature of the structure and this type of tuning may be called thermal tuning or simply T-tuning [20]. A photonic crystal having superconductor layer belongs to this type of PCs. This happens due to the temperature-dependent London perturbation length in the superconducting materials [21-24].

However, in earlier reports on the one dimensional PCs the researchers considered the dielectric media as temperature independent and non-dispersive. In this communication, the semiconductor media as one of the constituents of a one-dimensional photonic crystal is taken to be temperature and wavelength dependent. In the present studySi/air multilayer structure has been considered. The effect of temperature on refractive index of air is negligible small hence can be neglected. But the refractive index of semiconductor layer isaffected remarkably by temperature[25,26]. So, this multilayer system demonstrates big variation in refractive index contrast and this is very useful in photonics.

Theoretical Analysis

The schematic representation of the proposed one-dimensional photonic crystal is represented in Figure 1.

Figure 1: Schematic Diagram of 1-D Photonic crystal Structure



The proposed structure is air/(AB)^{N}A/air with A and B are the high and low refractive index materials. To compute the transmission/reflection spectra, the transfer matrix method (TMM) can be employed [27]. According to this method, the transfer matrix for each layer can be written as

$$M_j = D_j P_j D_j^{-1}; \qquad (1)$$

where, j stands for A or B layers and D_j and P_j are called the dynamical matrix and the propagation matrix respectively. The dynamical matrix can be written as the following equations

$$D_j = \begin{pmatrix} 1 & 1 \\ n_j \cos\theta_j & -n_j \cos\theta_j \end{pmatrix}$$

for TE mode of polarization (2)

and $$D_j = \begin{pmatrix} \cos\theta j & \cos\theta j \\ nj & -nj \end{pmatrix}$$

for TM mode of polarization (3)

Also, the propagation matrix P_j can be written as

$$P_j = \begin{pmatrix} e^{i\delta_j} & 0 \\ 0 & e^{-i\delta_j} \end{pmatrix} \qquad (4)$$

where the phase is written as

$$\delta_j = \frac{2\pi d_j}{\lambda} n_j \cos\theta_j \qquad (5)$$

The transfer matrix, for the air/(AB)^{N}A)^N/air structure can be written as

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_0^{-1}\left(M_A M_B\right)^N M_A D_0 \qquad (6)$$

Where, D_0 is called the dynamical matrix for air/vacuum.

Also, the reflection and transmission coefficients in terms of the matrix elements given in equation (6) can be written as

$$r = \frac{(M_{11}+q_f M_{12})q_i - (M_{21}+q_f M_{22})}{(M_{11}+q_f M_{12})q_i + (M_{21}+q_f M_{22})} \qquad (7)$$

And

$$t = \frac{2q_i}{(M_{11}+q_f M_{12})q_i + (M_{21}+q_f M_{22})} \qquad (8)$$

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 reflectance and transmittance of the structure is given by the following relation

$$R = |r|^2 \text{ and } T = |t|^2 \qquad (9)$$

Proposed Structure and Structural Parameters

Silicon is chosen for the material A and air for material Bas shown in Figure 1. Sowith the ten unit cells of Si/air, there will be the proposed structure; [air/(Si/air)^{10}Si/air]. The thicknesses of high and low refractive index materials are taken to be equal at 300K temperature i.e. $d_1 = d_2$. This study is performed in the temperature range from 300-700K.The thermal expansion coefficient of Si layer taken to be 2.6×10^{-6}/K and melting point taken to be 1685K [28]. The effect of temperature on refractive index of air is negligible small hence can be neglected. But the refractive index of semiconductor layer is affected remarkably by temperature. The refractive index of Silicon (Si) in the ranges of wavelength and temperature from 1.2 to 14 µm and 20-1600K respectively is taken as the experimental verification of H.H. Li [26].

Result and Discussion

Equation (10) is representing the relation of refractive index of Si with temperature and wavelength. The plot of the refractive index of Si as the function of wavelength and temperatureboth using H.H. Li data [26] is depicted in Figure 2. From this figure, it is clear that the refractive index of Si layers increase with temperature and decrease with wavelength. But the increment with temperature is remarkable and can be employed in band gap control. Therefore refractive index contrast (difference of refractive indices of two materials) increases with temperature. The variation of reflectance (color variation) with temperature at different temperatures is shown in Figure 3 and corresponding data are tabulated in Table 1.

Figure 2: Variation of Refractive index with wavelength and temperature for Silicon

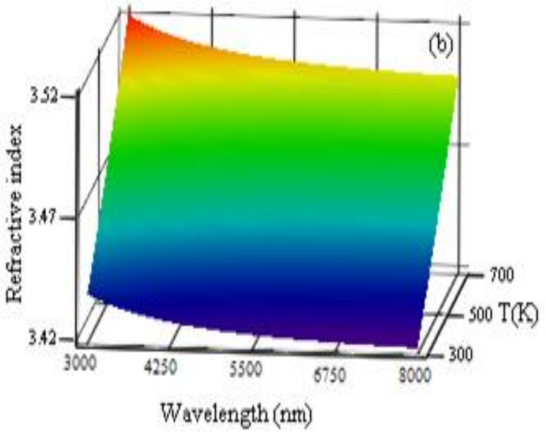
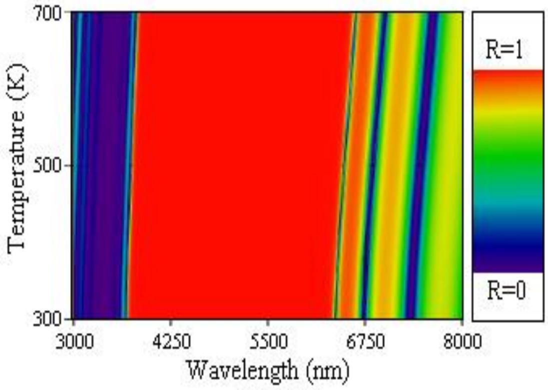


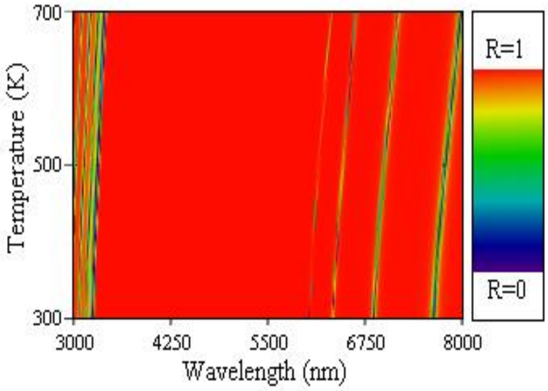
Table 1: PBG Width and Central Wavelength of Band-Gap at Different Angles of Incidence and Temperatures for Si/air Multilayer System

Temperature	300K		700K	
Angle of incidence	0°	85°	0°	85°
PBG width(nm)	2608	2782	2709	2903
Central wavelength(nm)	5037	4686	5258	4905

Figure 3: Reflectance with Temperature for Si/air Multilayer

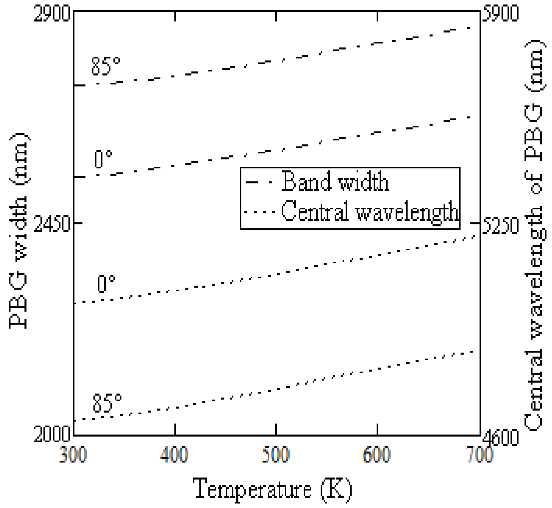


(a) θ=0°



(b) θ=85°

Figure 4: Variation of PBG Band Width and Central Wavelength of PBG with Temperature for Si/air



From Figure 3 it is observed that only one complete band gap (CPBG) appears in the reflection spectraof the proposed structure. From these Figures and Table, it is clear that this band gap shifts slightly towards the longer wavelength region with temperature (at constant angle of incidence). On the other hand,the band gaps shifts towards the shorter wavelength region with the angle of incidence (at constant temperature) but the PBG width increases with angle of incidence. The variation of PBG and band width as the function of temperature at different angles of incidence is shown in Figure 4. From this figure it is clear that the band width and center of these PBG increase but the central wavelength shifts towards the lower wavelength region for large angle of incidence with the increment in temperature.

This shifting behavior of allowed bands can be explained by the equation (5). As refractive index increases with temperature in R.H.S. of equation (5) [29-30], λ must increase to keep the L.H.S. unchanged. The shifting in PBG with incident angle is due to the cosine function on right hand side of equation (5). The value of the cosine function on right hand side of this equation decreases with the increment of the angle of incidence. So phase δ will be unchanged only when the wavelength decrease accordingly. This behavior of shifting this PBG is helpful in tuning the band width and central wavelength of this PBG.

Conclusion

The effect of the temperature as well as angle of incidence on the PBG for semiconductor-dielectric based photonic crystals has been investigated. The refractive indices of semiconductor (Si) layers are taken as the function of temperature and wavelength both. So, this study is useful for the wide range of temperature as well as wavelength. Therefore, this study is considered more physically realistic because of the temperature dependent and dispersive media. The proposed structure can be used as temperature sensing device, narrow band optical filter, wavelength division demultiplexer, tunable omni-directional reflector and in many optical systems.

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