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Broadening and tuning of omni-directional reflection gap in a 1D photonic crystal consisting semiconducting constituents

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ABSTRACT

The effect of temperature on omni-directional gap (ODG) in a dispersive one-dimensional photonic crystal has been investigated simultaneously considering thermal expansion effect and thermo-optic effect. The proposed structure consists of a periodic array of alternate layers of ZnS and Ge respectively, as the materials of low and high refractive index materials. The refractive index of both layers is taken as a function of temperature and wavelength both. The effect of temperature on ODR band and the central wavelength of this ODR have been studied. This ODR can be tuned by varying the temperature of the geometry. The propagation characteristics of the proposed structure are analyzed by the transfer matrix method.

1. Introduction

In recent years, 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 circumstances, photonic crystals can exhibit photonic band gaps (PBGs) i.e. certain range(s) of optical wavelengths that are forbidden to propagate inside the photonic crystal [1]. By introducing defect(s) in the periodic structure of the PCs, one can obtain a very narrow defect mode inside the band gap [2]. This unique feature of the photonic crystal structures alters dramatically the flow of light and manipulations of photons within such a structure and can lead to many potential applications in optics, optoelectronics and photonics [3–8]. 1D Photonic Crystal structures have many potential applications such as trapping of light [7], filters [8,9], WDM demultiplexer [10,11], switches [12], temperature sensor [13] etc. Theoretical and experimental demonstration of absolute omni-directional PBGs using have been done using one-dimensional PCs [14–17]. Omni-directional reflector has a unique property that it has 100% reflectivity at any angle of incidence for both TE and TM polarized electromagnetic waves.

Mostly, photonic crystals have been made from semiconductors and dielectrics. While the effects of temperature on semiconductors lead to the variation of refractive indices among other things, it can change various optical properties of PCs. Earlier reports on omni-directional reflection were primarily based on non-dispersive media and without the consideration of the thermal effect. In the present communication, we propose a simple design of an omni-directional reflector (ODR) using a one-dimensional photonic crystal that is designed using the temperature modulation of thickness (thermal expansion effect) and refractive index (thermo-optic effect) of each constituent layer. The proposed structure consists of a periodic array of alternate layers of ZnS and Ge respectively as the materials of low and high refractive indices. As the indices of refraction and thickness of each layer are modulated by temperature, the ODR band can be tuned to a desired wavelength by adjusting the temperature. To the best of our knowledge no other thermal tuning ODR based theoretical/or experimental work is available for the comparison.

2. Theoretical analysis

We consider a multilayered structure [air/$(n_1 n_2)^{10}$/air] which consists of alternate layers of materials of low and high refractive indices along the x-axis, as shown in Fig. 1.

Applying the transfer matrix method (TMM), the characteristic matrices for the TE and TM waves for a unit cell of such a structure have the form [18,19]

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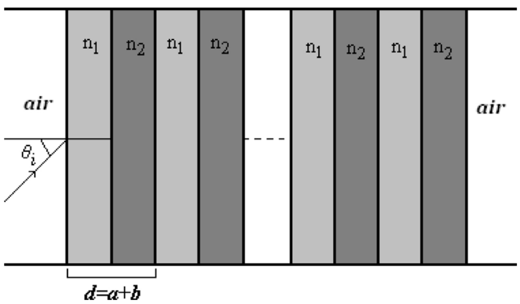

Fig. 1. Schematic diagram of 1-D photonic crystal structure.

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

where $q_j = n_j cos\theta_j$, $(j = 1,2)$ for the 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 (air). The characteristics matrix for the N unit cells is given by

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

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

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

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 correspond to the quantities respectively in the medium of incidence and the medium of emergence. Whereas, the reflectivity of the structure is given by

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

There is no absolute photonic band gap (PBGs) in 1D photonic crystal due to two factors. First is that the edges of the PBGs (more specifically PBGs at a certain direction) shifts toward the lower wavelength side with the increase in incident angle, and in generally leads to the disappearance of the overall PBGs. Second one is that, the TM mode cannot be reflected at Brewster angle. However, it does not mean that there is no omni-directional reflection band in 1D photonic crystal. Here 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].

2.1. Proposed structure and structural parameters

We take Ge and ZnS as the high and the low refractive index materials. The geometrical parameters are so chosen that the thicknesses of high and low refractive index materials at 300 K. The layer of Ge and ZnS will be expanding with the increase in temperature in the following manner;

$$a(T) = a(1 + \alpha\Delta T) \quad \text{and} \quad b(T) = b(1 + \beta\Delta T) \tag{5}$$

where α is the thermal expansion coefficient for Ge layer and taken to be 6.9×10^{-6}/K and β is the thermal expansion coefficient for ZnS layer and taken to be 6.1×10^{-6}/K [20]. The melting points for Ge and ZnS layers are 1210 K and 1830 K, respectively [20].

The refractive index of Ge layer is taken as a function of both wavelength and temperature. The refractive index of Ge in the ranges 1200–14,000 nm and 293–1000 K can be expressed as a function of both the wavelength and temperature as [21]

$$n_1{}^2(\lambda, T) = \varepsilon(T) + \frac{e^{-3\Delta L(T)/L_{293}}}{\lambda^2}(2.5381 + 1.8260 \times 10^{-3}T + 2.8888 \times 10^{-6}T^2) \tag{6}$$

where, $\varepsilon(T) = 15.2892 + 1.4549 \times 10^{-3}T + 3.5078 \times 10^{-6}T^2 - 1.2071 \times 10^{-9}T^3$ and $\frac{\Delta L(T)}{L_{293}} = 5.790 \times 10^{-5}(T - 293) + 1.768 \times 10^{-9}(T - 293)^2 - 4.562 \times 10^{-13}(T - 293)^3$ for $293\ \text{K} \le T \le 1000\ \text{K}$

Similarly, the refractive index of ZnS layer is taken as a function of both wavelength and temperature. The refractive index of ZnS in the ranges 1200–14,000 nm and 293–700 K can be expressed as a function of both the wavelength and temperature as [22]

$$n_2^2(\lambda, T) = \varepsilon_1(T) + \frac{A(T)}{\lambda^2 - \lambda_1^2} + \frac{B(T)}{(\lambda/\lambda_2)^2 - 1} \tag{7}$$

where $\lambda_1 = 0.23979 + 4.841 \times 10^{-5}T_1$, $\lambda_2 = 36.525 + 4.75 \times 10^{-3}T_1$ and $T_1 = T - 293$ and

$$\varepsilon_1(T) = 8.34096 + 1.29107 \times 10^{-3}T_1 + 4.68388 \times 10^{-7}T_1{}^2 - 1.31683 \times 10^{-9}T_1{}^3 - 6.64356 \times 10^{-12}T_1{}^4$$

$$A(T) = 0.14540 + 1.13319 \times 10^{-5}T_1 + 1.05932 \times 10^{-8}T_1^2 + 1.06004 \times 10^{-10}T_1^3 + 2.27671 \times 10^{-13}T_1^4$$

and

$$B(T) = 3.23924 + 1.096 \times 10^{-3}T_1 + 4.20092 \times 10^{-7}T_1^2 + 1.1135 \times 10^{-9}T_1^3 + 7.2992 \times 10^{-12}T_1^4$$

3. Results and discussion

From Eq. (4), the reflection properties of one-dimensional photonic crystals are computed considering thermal expansion effect and thermo-optic effect simultaneously. For this purpose, we consider the PC structure having $n_1(\lambda,T)$ and $n_2(\lambda,T)$ as refractive indices of ZnS and Ge respectively. The refractive indices are taken considering thermo-optic effect in Eqs. (6) and (7) for ZnS and Ge, respectively. The thickness of each layer is taken considering the effect of thermal expansion of each layer given by Eq. (5).

The thicknesses "a" and "b" of the consecutive layers are chosen such that $a = 584.63$ nm and $b = 326.82$ nm at 300 K temperature according to the quarter wave stack condition $a = \lambda_c/4n_1$ and $b = \lambda_c/4n_2$, corresponding to the critical wavelength, $\lambda_c = 5250$ nm. The critical wavelength is the mid-wavelength of the wavelength range considered in our numerical computation. We choose $n_1 = n_1(5250\ \text{nm}, 300\ \text{K}) = 2.245$ and $n_2 = n_2(5250\ \text{nm}, 300\ \text{K}) = 4.016$.

The plots of the refractive indices as the function of wavelength and temperature are shown in Fig. 2(a) and (b) for ZnS and Ge, respectively. From Fig. 2, it is clear that the refractive indices of both materials increase with temperature and decrease with wavelength. From these figures, it is clear that the change in refractive index of ZnS is 0.05 for a temperature change from 300 K to 700 K and the change in refractive index of Ge is 0.23 for the same change in temperature. Therefore, the refractive index contrast increases with temperature.

The reflectance spectra of the proposed PC (for both TE and TM polarizations) at 300 K, is shown in Fig. 3 and the data corresponding to nearly 100% reflectance is summarized in Table 1. We observe from Fig. 3 and Table 1 that the TE polarization has its