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Design of a thermally tunable optical filter based on one-dimensional ternary photonic band gap material

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ABSTRACT

Design: of a tunable band pass filter using one dimensional ternary periodic refractive index profile has been presented. Design of the proposed filter is based on the model of Kronig–Penny in solid state physics. In this present filter, the desired wavelength regions can be tuned by altering the temperature or the incidence angle. A Ge/Si/air multilayer system is considered here. The refractive indices of Si and Ge layers have been taken to be functions of temperature as well as wavelength. Due to the dependence of refractive indices of Si and Ge on temperature, transmission characteristic of the structure changed, and this property has been exploited to shift the transmission band. Hence, the proposed ternary structure can be utilised to tune the pass bands by changing the temperature or the incident angle. Detailed analysis shows that ternary structure gives better performance than the binary structure in terms of tunability.

1. Introduction

Photonic Crystals (PCs) that offer stop bands in the electromagnetic spectrum also called as photonic band gaps have been studied intensively over last two decades to analyse their primary physical characteristics as well as for their latent applications in modern optoelectronic devices. Photonic crystal (PCs) was first proposed by Yablonovitch and John independently in 1987 simultaneously [1,2]. After this, Photonic band gap materials have been widely investigated [3–6]. These materials are artificial structures in which materials have a periodically changing refractive index profile on the length scale of the order of optical wavelength. The Fiber Bragg Grating is the Simplest PBG structure is the and is extensively used in optical communication systems. Existence of forbidden bandgap in their transmission spectra is the main importance of PBGs, which does not exist in bulk materials. A photonic band gap in a photonic crystal (PC) is analogous to the electronic band gap in a solid. Photonic crystals have wide range of applications like optical filters [7–10], omnidirectional reflectors [11,12], DWDM applications [13–19], temperature sensors [20], trapping of light [21], optical switches [22–28] etc.

We have presented a design of thermally tunable filter using Silicon [9]. Design of this filter was based on the Kronig–Penny model with binary structure. In this design, we have used binary layer periodic structure in the designing of filter. Average tuning or shift in central wavelength in this design tuning was 0.08–0.16 nm/K for different allowed bands at normal incidence. In the present communication, design of a thermally tunable optical filter based on ternary layer one-dimensional periodic structure has been presented. Present filter is also based on the same model, but with ternary structure. In this design also, we have explored the temperature dependency of refractive index in Germanium and Silicon, but in ternary structure. It was found that the filter based on ternary structure layer gives better performance in comparison to binary layer structure.

2. Theoretical analysis

In this study the propagation of electromagnetic waves in a one dimensional periodic structure is considered along z-axis and we select this z-axis in such a manner that it is normal to the layers. The periodic refractive index profile of the one dimensional periodic structure based on ternary layer considered here are given by [8]

$$n(z) = \begin{cases} n_1 & 0 \prec z \prec d_1 \\ n_2 & 0 \prec z \prec d_2 \\ n_3 & 0 \prec z \prec d_3 \end{cases} \quad (1)$$

with $n(z) = n\ (z + md)$, where $m = 0, \pm 1, \pm 2, \pm 3, \ldots$. Here $d = d_1 + d_2 + d_3$ is the lattice period of the structure with width d_1, d_2 and d_3 of the three layers having n_1, n_2, and n_3 refractive indices, respectively. The z axis is the perpendicular to the layer interface.

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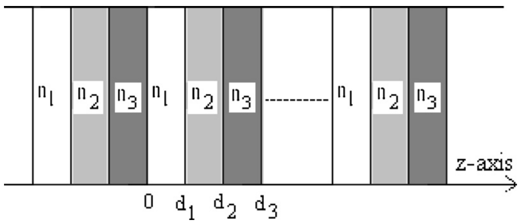

Fig. 1. Periodic refractive index profile of the proposed structure.

The schematic view of the structure considered here is illustrated in Fig. 1.

Equation of an electromagnetic wave propagating along the z-axis may be written as

$$\frac{d^2\psi_k(z)}{dz^2} + \frac{{n_i}^2(z)\cdot\omega_k^2}{c^2}\psi_k(z) = 0 \tag{2}$$

where n is expressed in Eq. (1).

Due to the periodic nature of the problem considered here, we can use Bloch's theorem, which solution can be expressed as

$$\psi_K(z) = u_K(z)e^{iKz} \tag{3}$$

where $u_K(z)$ is the eigen function and K is Bloch wave number. Using this theorem if we solve Eq. (2) for eigenvalues of the wavelengths, we finally gets the following relation [8,29]

$$L(\lambda_0) = \cos(kd) \tag{4}$$

where the LHS $L(\lambda_0)$ can be written as

$$L(\lambda_0) = \cos(\beta_1)\cdot\cos(\beta_2)\cdot\cos(\beta_3) - \frac{1}{2}\left(\frac{p_2}{p_1}+\frac{p_1}{p_2}\right)\cdot\sin(\beta_1)\cdot\sin(\beta_2)\cdot\cos(\beta_3)$$
$$-\frac{1}{2}\left(\frac{p_2}{p_3}+\frac{p_3}{p_2}\right)\cdot\cos(\beta_1)\cdot\sin(\beta_2)\cdot\sin(\beta_3) - \frac{1}{2}\left(\frac{p_1}{p_3}+\frac{p_3}{p_1}\right)\cdot\sin(\beta_1)\cdot\cos(\beta_2)\cdot\sin(\beta_3) \tag{5}$$

where

$$\beta_1 = \frac{2\pi n_1 d_1}{\lambda_0}\left(1-\frac{\sin^2\theta}{{n_1}^2}\right)^{1/2} \qquad \beta_2 = \frac{2\pi n_2 d_2}{\lambda_0}\left(1-\frac{\sin^2\theta}{{n_2}^2}\right)^{1/2}$$

$$\beta_3 = \frac{2\pi n_3 d_3}{\lambda_0}\left(1-\frac{\sin^2\theta}{{n_3}^2}\right)^{1/2} \qquad p_1 = {n_1}^2\left(1-\frac{\sin^2\theta}{{n_1}^2}\right)^{1/2}$$

$$p_2 = {n_2}^2\left(1-\frac{\sin^2\theta}{{n_2}^2}\right)^{1/2} \qquad p_3 = {n_3}^2\left(1-\frac{\sin^2\theta}{{n_3}^2}\right)^{1/2}$$

Due to presence of cosine function on right hand side of Eq. (4), maximum and minimum values of this equation will be +1 and −1, respectively.

3. Proposed structure and structural parameters

For design and simulation of the filter, air, Germanium and Silicon has been chosen as the materials of the alternate layers of ternary multilayer structure. The geometrical parameters of the purposed structure are chosen such that the thickness of air, Germanium and Silicon is $d_1 = 0.80d$, $d_2 = 0.80\times(0.20d)$ and $d_3 = 0.20\times(0.20d)$, respectively. Here $d = d_1 + d_2 + d_3 = 700$ nm, is the lattice period.

The refractive indices of Germanium and Silicon are taken to be temperature dependent [30], on the other hand refractive index of air is taken to be 1 and independent of the temperature. The refractive index of Germanium in the wavelength range 1.2–14 μm and temperature range 293–1000 K is given by [30]

$$n^2(\lambda, T) = \varepsilon(T) + \frac{e^{-3\Delta L(T)/L_{293}}}{\lambda^2} \times \left(2.5381 + 1.8260\times10^{-3}T + 2.8888\times10^{-6}T^2\right) \tag{6}$$

where

$$\varepsilon(T) = 15.2892 + 1.4549\times10^{-3}T + 3.5078\times10^{-6}T^2 - 1.2071\times10^{-9}T^3$$

$$\frac{\Delta L(T)}{L_{293}} = 5.790\times10^{-3}(T-293) + 1.768\times10^{-9}(T-293)^2 - 4.562\times10^{-13}(T-293)^3$$

For 293 K ≤ T ≤ 1000 K.

Refractive index of Silicon in the wavelength range 1.2–14 μm and temperature range 293–1600 K is given by [30]

$$n^2(\lambda, T) = \varepsilon(T) + \frac{e^{-3\Delta L(T)/L_{293}}}{\lambda^2} \times \left(0.8948 + 4.3977\times10^{-4}T + 7.3835\times10^{-8}T^2\right) \tag{7}$$

where

$$\varepsilon(T) = 11.4445 + 2.7739\times10^{-4}T + 1.7050\times10^{-6}T^2 - 8.134710^{-10}T^3$$

$$\frac{\Delta L(T)}{L_{293}} = -0.00071 + 1.887\times10^{-6}T + 1.934\times10^{-9}T^2 - 4.554\times10^{-13}T^3$$

For 293 K ≤ T ≤ 1600 K.

4. Result and discussion

In this section, result of the simulation of the proposed structure has been presented. Simulation of the proposed structure has been performed for the various angel of incidence at constant temperature, and for different temperatures at normal incidence.

Using the expression of refractive indices of Germanium and Silicon, behaviour of function $L(\lambda_0)$ is studied with respect to the for at the four different angel of incidence at constant temperature. For this purpose, a graph between $L(\lambda_0)$ and free space wavelength λ_0 is plotted. Same method has been applied to study behaviour of the structure at different temperatures for normal incidence. Figs. 2 and 3 show the plots of $L(\lambda_0)$ for the two cases, and Tables 1 and 2 show the corresponding data in tabulated form. It is observed from Eq. (4) that due to the presence of cosine function in the right hand side lies between +1 & −1. Thus, the region for which $L(\lambda_0)$ lies between +1 & −1, is known as pass band of wavelength and the region for which $L(\lambda_0)$ lies outside +1 & −1 is called stop band of wavelength. The consequential graphs at four different incident angles at same temperature 300 K are shown in Fig. 2 and resultant data is tabulated in Table 1. It is observed from Fig. 2 and Table 1 that when electromagnetic radiations having wavelengths from 1200 nm to 3600 nm are allowed to incident on the ternary