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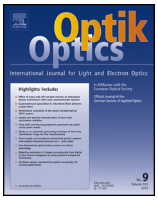

One-dimensional nano layered SiC/TiO$_2$ based photonic band gap materials as temperature sensor

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ABSTRACT

In this present paper, we have proposed a novel design of temperature sensor using 1-dimensional photonic band gap materials, which is made by alternate layers of TiO$_2$ and silicon carbide (4H–SiC) with periodic variation of their respective thickness and refractive indices. We have investigated the reflection properties, relative band width behaviour and group velocity of the proposed photonic band gap materials at different temperature. The refractive index of SiC is temperature dependent, so by increasing the temperature the number of forbidden bands as well as width of the forbidden bands increases and the value of group velocity decreases. Thus, by analysing the band gap width, number of forbidden bands, and group velocity, it is easy to calculate the value of temperature of the given environment. This paper is focused on what we regard the latest development in the use of photonic band gap materials in photonic devices, a strong importance with the application in communication. It may be used as a temperature sensor. Our results show the potential application in temperature controlled optoelectronic devices.

1. Introduction

Photonic crystals have attracted much attention in the field of optical physics due to its peculiar optical properties. Photonic crystals are the periodic dielectric structure in one, two, and three dimensions. These structures are based on the interaction between an optical field and material exhibiting periodicity on scale of wavelength of radiation; allow guiding and manipulating the flow of light on this scale [1,2]. One-dimensional photonic crystals are more frequently studied by the people because it is easy to fabricate and handle. A lot of research work has been done on one-dimensional photonic crystal [3–7]. One-dimensional photonic crystals play a crucial role in material adulteration sensor, temperature sensor and refractometer systems [8,9]. Photonic devices offer very high speed of operation, tolerance to temperature fluctuations, increased life time, and the capability to care high repetition rates compared to conventional electronic devices. All these devices work on the principle of photonic band edge and they are extremely compendious in structure [10–12].

The photonic band gap arises due to the coherence effect of scattering and interference, which occurs in dispersion relation for light travelling in the composite of the proposed structure. The absence of electromagnetic wave, inside photonic band gap will lead to some unusual properties, which can be used for Bragg mirrors, narrow band filters etc. [13,14]. There are several phenomena, which makes, the photonic band edge much interesting such as rapid transition from low transmission zone to high transmission zone. It can be widely used in decreasing the group velocity of light less than the velocity of light in vacuum. This property plays a crucial role in short pulse laser compression, optical buffering, switching components etc. [15–19]. The localization of light increases the interaction of light with matter, which gives several interesting phenomenon such as nonlinear optics [20,21] and magneto optics [22,23].

Significant development has been done over the past decades in the area of wide band gap semiconductor materials. SiC is one of the best materials in the wide band gap semiconductor. It has better prospect for the device implementation. Single crystal SiC(4H–SiC), has various interesting optical properties such as wide band gap, high thermal stability, high mechanical strength, high oxidation and corrosion resistance and high sensing capability, which makes it very important in optoelectronic devices. Usually at high temperature, most of the semiconductors change their nature, that is why they cannot be used in devices operating at high temperature. Due to this reason SiC is widely used as optical sensor at elevated temperature because of its high thermal stable capacity compared to other dielectric materials [24–26]. The optical sensor made up of SiC have been easily employed at temperature above 300 °C. The wide band gap, high thermal conductivity and chemical

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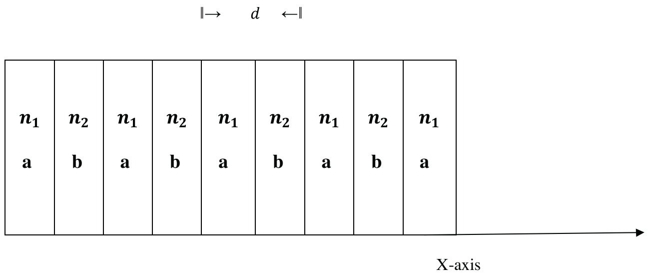

Fig. 1. Periodic variation of the refractive index profile in the form of rectangular structure.

inertness make SiC as optical sensing material for abrasive environment [27–31]. In addition, SiC is widely used as UV detector, ultraviolet photodetector, high temperature photodetector, blue and violet light emitting diodes. It is also utilized in the field of gas sensor and telecommunication.

In this paper, we have taken one dimensional photonic crystal having alternate layers of TiO_2 and silicon carbide (SiC). Using the transfer matrix method [32,33], we have calculated the reflectance spectra and relative bandwidth of the proposed structure. We have also investigated the group velocity, of the proposed structure by using Thelen's theory [34–37]. By increasing the value of temperature the number of forbidden bands and bandwidth increases simultaneously. In this case the value of group velocity reduces by increasing the value of temperature. It may be widely used as temperature sensor, since its optical properties changes by changing the temperature. It can be used in numerous optoelectronics and photonic devices.

2. Theoretical details

To study, the propagation characteristics of electromagnetic waves through the periodic structure of TiO_2 and SiC (4H–SiC) whose refractive indices are n_1 and n_2 respectively, we select the particular x-axis through the material along the direction normal to the layers as shown in Fig. 1. The refractive index profile of this periodic structure is given by

$$n(x) = \begin{cases} n_1, & 0 \le x \le a; \\ n_2, & -b \le x \le 0; \end{cases} \tag{1}$$

with $n(x+d) = n(x)$, $d = a + b$ where d is the thickness of the period, a and b are the thickness of the alternate layers of TiO_2 and SiC with refractive indices n_1 and n_2.

In this section the refractive index of 4H–SiC has been analysed with the change in environmental condition such as temperature and pressure.

For normal incidence of radiation the phase angle is given by

$$\phi = 2\pi \frac{n(T,P)d(T,P)}{\lambda} \tag{2}$$

where $n(T,P)$ is the refractive index of the SiC, $d(T,P)$ is the thickness of the sample and λ is the wavelength of used radiation. T and P are the temperature and pressure of environment. The refractive index of SiC, $n(T,P)$, is wavelength dependent due to the dispersion, temperature dependent due to the thermooptic effect, and pressure dependent due to the stress [38–42]. With the help of Eq. (2), the phase shift in SiC is given as

$$\Delta\phi = \frac{2\pi d(T,P)}{\lambda} \Delta n(T,P) + \frac{2\pi n(T,P)}{\lambda} \Delta d(T,P) \tag{3}$$

where $d(T,\ P) = [1 - (\Delta P/E)]$, $\Delta d(T,\ P) = d_0 \alpha_{mid}(\Delta T) - (d_0/E)(\Delta P)$, d_0 is the initial thickness of SiC, E is the Young's modulus, $\Delta T = T_{m+1} - T_m$, m is an integer, $\Delta P = P_1 - P_0$, P_1 is the pressure at which the sensor response was carried on, P_0 is the initial value of atmospheric pressure, n_{m+1} is the value of refractive index at temperature T_{m+1}, n_m is the value of refractive index at temperature T_m•n_m and n_{m+1} for a fixed wavelength can be expressed by following relationship

$$n_m = n(T_m, P)$$

$$n_{m+1} = \frac{\lambda_0 + n_m d_0 \left[2 - (1/E)(\Delta P) - \alpha_{mid}(\Delta T)\right]}{d_0[2 - (3/E)(\Delta P) + \alpha_{mid}(\Delta T)]} \tag{4}$$

where λ_0 is the free space wavelength, α_{mid} is thermal expansion coefficient of SiC at temperature T_{mid} and can be expressed as $\alpha_{mid} = \alpha[(T_m + T_{m+1})/2]$

Eq. (4) can be used to determine the value of refractive index at high value of temperature and pressure. At constant pressure, we have calculated the temperature dependent refractive index between the temperature range 20 and 375 °C. The SiC acts as an amplitude splitting device. It may be considered as two coherent virtual sources lying between the SiC wafer. In SiC the optical path difference between two adjacent reflected beam is given by $\Lambda = 2 n_{SiC} d \cos\theta_t$, where Λ is optical path length, n_{SiC} is refractive index of SiC, d is the thickness of the sample and θ_t is the transmitted angle. The value of d is affected by the temperature due to the thermal expansion. The thermal expansion coefficient of SiC is given as $\alpha(T) = 3.19 \times 10^{-6} + 3.60 \times 10^{-9} T - 1.68 \times 10^{-12} T^2$

To solve the propagation characteristics of electromagnetic radiation in the proposed structure, we use 2 × 2 transfer matrix approach. The electric field of a general plane-wave solution of the wave equation can be written as

$$E = E(x) e^{i(\omega t - \beta z)} \tag{5}$$

where β is the z component of the wave vector and ω is the angular frequency.

The electric field in each layer is expressed as the sum of incidence plane wave and reflected plane wave. The nth and $(n-1)$th unit cell coefficients can be expressed in the form of the matrix, which is given by

$$\begin{pmatrix} a_{n-1} \\ b_{n-1} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} a_n \\ b_n \end{pmatrix} \tag{6}$$

The matrix elements are

$$A = e^{ik_1 a} \left[\cos k_2 b + \left(\frac{1}{2}\right) i \left(\frac{k_2}{k_1} + \frac{k_1}{k_2}\right) \sin k_2 b\right],$$

$$B = e^{-ik_1 a} \left[+ \left(\frac{1}{2}\right) i \left(\frac{k_2}{k_1} - \frac{k_1}{k_2}\right) \sin k_2 b\right],$$

$$C = e^{ik_1 a} \left[- \left(\frac{1}{2}\right) i \left(\frac{k_2}{k_1} - \frac{k_1}{k_2}\right) \sin k_2 b\right],$$

$$D = e^{-ik_1 a} \left[\cos k_2 b - \left(\frac{1}{2}\right) i \left(\frac{k_2}{k_1} + \frac{k_1}{k_2}\right) \sin k_2 b\right],$$

The reflection coefficient of the periodic layered medium that consist of N periods (i.e., N pair of layers) is given by

$$r_N = \left(\frac{b_0}{a_0}\right)_{b_N = 0} \tag{7}$$

As we know that, only one column vector is independent. We can choose it, as an example, as the column vector of the n_1 layer in the zeroth period. The remaining column vectors of the periodic layers are given by

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^N \begin{pmatrix} a_N \\ B_N \end{pmatrix} \tag{8}$$