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ENHANCED TEMPERATURE SENSING BY USING ONE-DIMENSIONAL TERNARY PHOTONIC BAND GAP STRUCTURES

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Abstract—This paper demonstrates a novel way to enhance the temperature sensitivity in one-dimensional (1D) photonic band gap (PBG) material by using a ternary periodic structure (i.e., three material layers constituting a period of lattice). The temperature sensitive wavelength band shift of (Si/SiO_2) periodic structure was significantly enhanced when the structure was modified by sandwiching a thin layer of $Bi_4Ge_3O_{12}$ between every two layers, constituting a period of lattice. When the thickness of sandwiched layer was increased further enhancement in temperature sensitivity was observed. These 1D ternary PBG structures can be substituted in place of 1D binary PBG structures for enhancing the temperature sensing performance.

1. INTRODUCTION

One-dimensional (1D) periodic binary photonic band gap (PBG) structures [1, 2] have been the subject of interest in recent years. These 1D periodic binary PBG structures are multilayer structures formed by using two materials. These periodic multilayer structures lead to formation of photonic band gaps or stop bands, in which propagation of electromagnetic waves of certain wavelengths are prohibited. These bands or ranges depend upon a number of parameters such as refractive indices of materials, thicknesses of material layers and angle of incidence etc. [3]. If all these parameters are kept constant, then this 1D PBG structure will have fixed predetermined bands of wavelengths or frequencies which will be reflected or transmitted by the structure.

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However, when the temperature varies, the refractive index of the medium will be changed due to thermo-optical effect. On the other hand, the thermal expansion effect will induce the thickness change of the medium. In this case, the band structure will be varied. By monitoring transmission or reflection band change or shift, a change in temperature can be detected. In this way these 1D PBG structures can be used as a temperature sensing element. Recently, Kai et al. [4] studied temperature property of band structures in 1D binary PBG structures and found that changes of the starting wavelength, the cut off wavelength and the forbidden band width depend linearly on the temperature. These researchers [4] also suggested application of 1D binary PBG structures in temperature sensing.

Recently, 1D periodic ternary PBG structures attracted attention of researchers due to their superior performance over 1D periodic binary PBG structures in omni directional reflection [5], tunable optical filtering [6] and refractometric optical sensing [7]. These 1D ternary PBG structures are formed by periodic repetition of three different material layers instead of two different materials as in case of conventional 1D binary PBG structures. Actually PBG structures can be classified into categories like binary, ternary, quaternary or so on, according to the number of layers in one period. Binary photonic crystal contains two layers in a period, ternary photonic crystal contains three layers in a period, quaternary photonic crystal contains four layers in a period and so on. Finally, these periods are repeated several times to form PBG structures.

These 1D ternary PBG structures are not only superior omni directional reflectors [5], tunable optical filters [6] and refractometric optical sensing elements [7], but in this communication, it is shown that they are superior temperature sensing elements also, when compared with 1D binary PBG structure [4]. This paper reports an enhancement in the temperature sensing performance when a ternary PBG structure is used. The approach is simple; the binary structure can be modified to form a ternary structure by sandwiching a thin layer of a third material between the two layers of the binary structure periodically to form a ternary photonic crystal.

2. THEORY

The binary photonic crystal consisting of alternate layers of refractive indices n_1 and n_2 with thicknesses d_1 and d_2 respectively is depicted in Figure 1. $d = d_1 + d_2$ is the period of the lattice.

The binary structure shown in Figure 1 can be modified by sandwiching a thin layer of a third material of refractive index n_B and thickness d_B between two layers of the binary structure periodically to form a ternary photonic crystal as depicted in Figure 2. Now this modified periodic structure (i.e., ternary structure) has alternate layers of refractive indices n_1 (first material layer), n_B (second material layer) and n_2 (third material layer) with thicknesses: d_1, d_B and d_2 respectively. $d = d_1 + d_B + d_2$ is the period of the lattice.

It is well known that the thickness and refractive index of medium can be changed due to thermal expansion effect and thermo-optical effect. In certain temperature range, the thermal-expansion of any material layer is given by

$$\Delta d = \alpha d \left(\Delta T\right) \tag{1}$$

where, α represents the thermal expansion coefficient of the medium, and ΔT indicates the variation of the temperature.

Due to thermo-optical effect, the refractive index change of any material layer is

$$\Delta n = \gamma n \left(\Delta T\right) \tag{2}$$

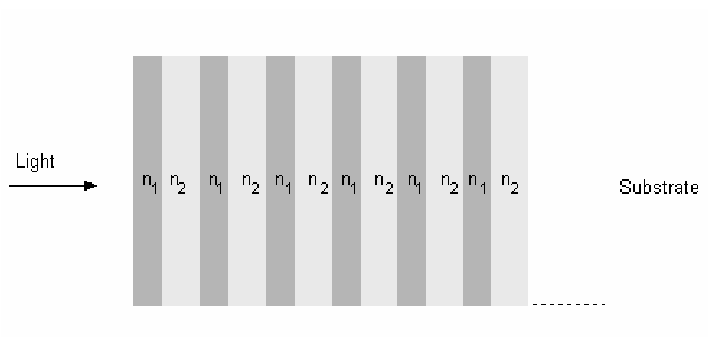

Figure 1. Schematic of 1D binary PBG structure.

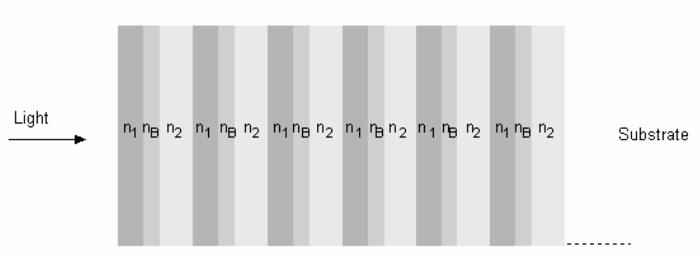

Figure 2. Schematic of 1D ternary PBG structure.

where, γ is the thermo-optic coefficient of the medium.

According to the optical transmission matrix theory [8], for light incident from air on the multilayer at an angle θ_0; for the s wave, the characteristic matrix $M[d]$ of one period is given by

$$M\left[d\right] = \prod_{i=1}^{l} \begin{bmatrix} \cos\beta_i & \frac{-i\sin\beta_i}{p_i} \\ -ip_i\sin\beta_i & \cos\beta_i \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{3}$$

where, $l = 3$ (1, 2 and 3 signify the layers of refractive indices n_1, n_B and n_2 respectively). By incorporating the changed refractive indices and thicknesses

$$\beta_1 = \frac{2\pi\left(n_1+\Delta n_1\right)\left(d_1+\Delta d_1\right)\cos\theta_1}{\lambda_0},$$
$$\beta_2 = \frac{2\pi\left(n_B+\Delta n_B\right)\left(d_B+\Delta d_B\right)\cos\theta_2}{\lambda_0},$$
$$\beta_3 = \frac{2\pi\left(n_2+\Delta n_2\right)\left(d_2+\Delta d_2\right)\cos\theta_3}{\lambda_0},$$

λ_0 is the free space wavelength, $p_1 = (n_1+\Delta n_1)\cos\theta_1$, $p_2 = (n_B+\Delta n_B)\cos\theta_2$ and $p_3 = (n_2+\Delta n_2)\cos\theta_3$. θ_1, θ_2 and θ_3 are the ray angles inside the layers 1, 2 and 3 respectively and are related to the angle of incidence θ_0 by

$$\begin{aligned} \cos\theta_1 &= \left[1-\frac{\sin^2\theta_0}{\left(n_1+\Delta n_1\right)^2}\right]^{\frac{1}{2}}, \\ \cos\theta_2 &= \left[1-\frac{\sin^2\theta_0}{\left(n_B+\Delta n_B\right)^2}\right]^{\frac{1}{2}} \\ \text{and}\quad \cos\theta_3 &= \left[1-\frac{\sin^2\theta_0}{\left(n_2+\Delta n_2\right)^2}\right]^{\frac{1}{2}} \end{aligned} \tag{4}$$

The matrix $M[d]$ in Equation (3) is unimodular as $|M[d]| = 1$.

For an N period structure, the characteristic matrix of the medium is given by

$$\begin{aligned} \left[M\left(d\right)\right]^N &= \begin{bmatrix} M_{11}U_{N-1}\left(a\right)-U_{N-2}\left(a\right) & M_{12}U_{N-1}\left(a\right) \\ M_{21}U_{N-1}\left(a\right) & M_{22}U_{N-1}\left(a\right)-U_{N-2}\left(a\right) \end{bmatrix} \\ &\equiv \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \end{aligned}$$

where,

$$M_{11} = \left(\cos\beta_1\cos\beta_2\cos\beta_3 - \frac{p_2\sin\beta_1\sin\beta_2\cos\beta_3}{p_1} - \frac{p_3\cos\beta_1\sin\beta_2\sin\beta_3}{p_2} - \frac{p_3\sin\beta_1\cos\beta_2\sin\beta_3}{p_1}\right)$$

$$M_{12} = -i\left(\frac{\sin\beta_1\cos\beta_2\cos\beta_3}{p_1} + \frac{\cos\beta_1\sin\beta_2\cos\beta_3}{p_2} + \frac{\cos\beta_1\cos\beta_2\sin\beta_3}{p_3} - \frac{p_2\sin\beta_1\sin\beta_2\sin\beta_3}{p_1p_3}\right)$$

$$M_{21} = -i\left(p_1\sin\beta_1\cos\beta_2\cos\beta_3 + p_2\cos\beta_1\sin\beta_2\cos\beta_3 + p_3\cos\beta_1\cos\beta_2\sin\beta_3 - \frac{p_1p_3\sin\beta_1\sin\beta_2\sin\beta_3}{p_2}\right)$$

$$M_{22} = \left(\cos\beta_1\cos\beta_2\cos\beta_3 - \frac{p_1\sin\beta_1\sin\beta_2\cos\beta_3}{p_2} - \frac{p_2\cos\beta_1\sin\beta_2\sin\beta_3}{p_3} - \frac{p_1\sin\beta_1\cos\beta_2\sin\beta_3}{p_3}\right)$$

U_N are the Chebyshev polynomials of the second kind

$$U_N(a) = \frac{\sin[(N+1)\cos^{-1}a]}{[1-a^2]^{\frac{1}{2}}} \tag{5}$$

where,

$$a = \frac{1}{2}[M_{11} + M_{22}] \tag{6}$$

The transmission coefficient of the multilayer is given by

$$t = \frac{2p_0}{(m_{11} + m_{12}p_0)\,p_0 + (m_{21} + m_{22}p_0)} \tag{7}$$

and the transmissivity for this structure can be written in terms of transmission coefficient as

$$T = |t|^2 \tag{8}$$

where, $p_0 = n_0\cos\theta_0 = \cos\theta_0$ as $(n_0 = 1)$.

The transmissivity of the structure, for p wave can be obtained by using expressions (3)–(8) with the following values of p

$$p_1 = \frac{\cos\theta_1}{(n_1 + \Delta n_1)}, \quad p_2 = \frac{\cos\theta_2}{(n_B + \Delta n_B)},$$

$$p_3 = \frac{\cos\theta_3}{(n_2 + \Delta n_2)} \quad \text{and} \quad p_0 = \cos\theta_0.$$

3. RESULTS AND DISCUSSION

For normal incidence of light, the output spectra for 1D binary PBG structure at 25°C, 125°C, 225°C and 325°C are shown in Figure 3. The values of various parameters for this 1D binary PBG structure were chosen as [4] $n_1 = 3.3$ (Si), $n_2 = 1.46$ (SiO_2), $d_1 = 117\,\text{nm}$, $d_2 = 265\,\text{nm}$ and $N = 10$ at 25°C. The thermo-optic coefficient of Si is $1.86 \times 10^{-4}/°\text{C}$ and SiO_2 is $6.8 \times 10^{-6}/°\text{C}$. The thermal expansion coefficients are $0.5\times10^{-6}/°\text{C}$ and $2.6\times10^{-6}/°\text{C}$ respectively. Considering the transmission peak on the right side of the photonic band edge, it was found that the transmission peak shifts by 0.350 nm towards higher wavelengths with per degree rise in temperature. Figure 4 shows the output spectra for the ternary $Si/Bi_4Ge_3O_{12}/SiO_2$ PBG structure at 25°C, 125°C, 225°C and 325°C for normal incidence of light. The values of various parameters for this 1D ternary PBG structure were chosen as $n_1 = 3.3$ (Si), $n_B = 2.05$ ($Bi_4Ge_3O_{12}$), $n_2 = 1.46$ (SiO_2), $d_1 = 117\,\text{nm}$, $d_B = 10\,\text{nm}$, $d_2 = 265\,\text{nm}$ and $N = 10$

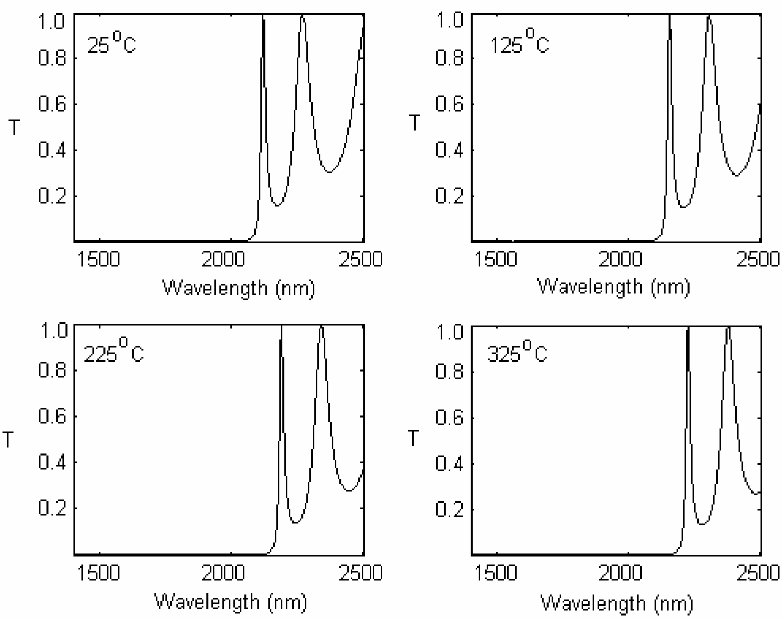

Figure 3. Transmission spectra for 1D binary PBG structure with $n_1 = 3.3$ (Si), $n_2 = 1.46$ (SiO_2), $d_1 = 117\,\text{nm}$ and $d_2 = 265\,\text{nm}$, $N = 10$ at 25°C, 125°C, 225°C and 325°C.

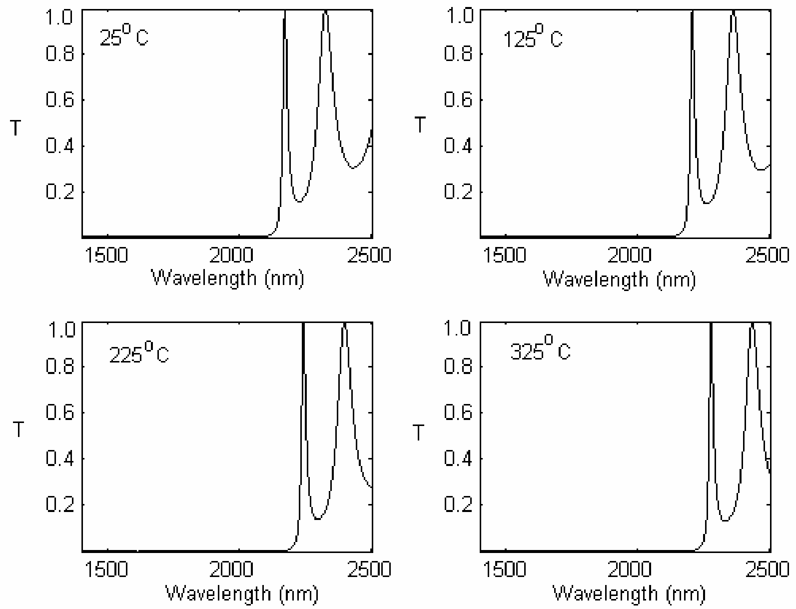

Figure 4. Transmission spectra for 1D ternary PBG structure with $n_1 = 3.3$ (Si), $n_B = 2.05$ ($Bi_4Ge_3O_{12}$), $n_2 = 1.46$ (SiO_2), $d_1 = 117\,\text{nm}$, $d_B = 10\,\text{nm}$ and $d_2 = 265\,\text{nm}$, $N = 10$ at 25°C, 125°C, 225°C and 325°C.

at 25°C. The thermo-optic coefficient of $Bi_4Ge_3O_{12}$ is 3.5×10^{-5}/°C. While, the thermal expansion coefficient of $Bi_4Ge_3O_{12}$ is 6.3×10^{-6}/°C. Here, in this case it was found that transmission peak shifts by 0.355 nm towards higher wavelengths with per degree rise in temperature. The temperature sensitive transmission peak shift of (Si/SiO_2) periodic structure was enhanced by 0.005 nm per degree when the structure was modified by sandwiching a thin layer of $Bi_4Ge_3O_{12}$ between every two layers, constituting a period of lattice.

The investigation was then repeated by taking $d_B = 50\,\text{nm}$, 100 nm and 150 nm. When the thickness of sandwiched layer was increased to 50 nm, the transmission peak shifted by 0.369 nm with per degree rise in temperature. Similarly, when the thicknesses of sandwiched layers were increased to 100 nm and 150 nm, the transmission peak shifted by 0.385 nm and 0.400 nm respectively with per degree rise in temperature. It was also found that the thermo-optic effect was dominant over the thermal expansion effect in shifting the

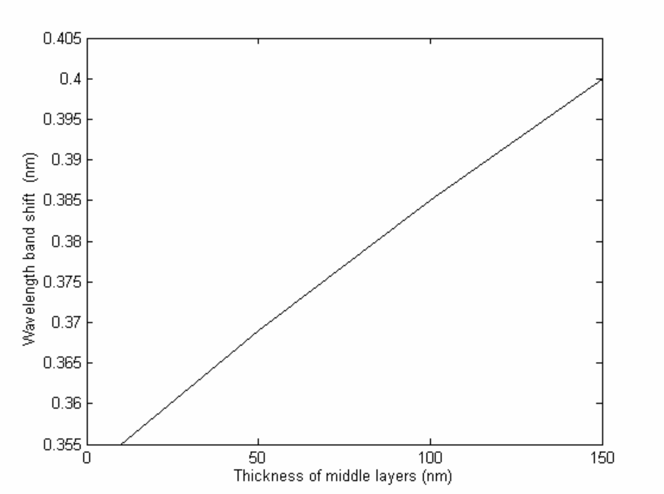

Figure 5. Effect of thickness of sandwiched layers on the transmission peak shift.

transmission peak or the band edge of the PBG structure. Figure 5 shows the effect of the thicknesses of Bismuth Geramante layer on the transmission peak shifts at a fixed temperature. It is clearly evident from this figure that transmission peak shift increases linearly with the increasing thickness of the Bismuth Germanate layer at a given temperature. So by selecting the proper thickness of this layer, desired temperature sensitivity with 1D ternary PBG structure can be achieved. These transmission peak or band shifts are very easily detectable with existing optoelectronic devices and the corresponding temperature change can be very easily known.

4. CONCLUSIONS

A novel way to enhance temperature sensing performance by using 1D ternary PBG has been suggested. The superiority of 1D ternary photonic crystal over 1D binary photonic crystal has been established for the temperature sensing application. Slight change in temperature in the ternary structure causes a sufficiently large transmission peak shift, which can be very easily detected by monitoring the transmission spectrum, with the help of existing optoelectronic devices. The sensitivity of 1D ternary photonic crystal can be controlled and enhanced by changing the thickness of the sandwiched layer. These 1D ternary PBG structures are superior substitutes of 1D binary PBG structures where enhanced sensing performance is required.

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