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Research Article

Realization Of Temperature Measurement Using Semiconductor Based Photonic Crystal Structure

Sakti Prasan Mohanty[1], KaliprasannaSwain[2], Sushant Kumar Sahoo[1], GopinathPalai[2*]

[1]Department of Physics, Kalinga Institute of Industrial Technology (KIIT), Deemed to be University, Bhubaneswar, 751024, India, saqti.m@gmail.com, physushant@gmail.com
[2]Department of ECE, GITA, Bhubaneswar, 752054, India, kaleep.swain@gmail.com, gpalai@gmail.com

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Abstract:
Semiconductor based two-dimensional triangular photonic crystal structures (TPCS) are focused in the present research to measure the temperature where the semiconductors like Silicon, Germanium, Indium Arsenide, and Indium Antimonide are used as the background materials. The triangular strctures are exposed to a light source of wavelength 10.59μm to estimate the temperatures. Since the abosorbtance of the background materials is zero at incident signal,the energy of transmitted light solely depends on the reflected light energy. Further plane wave expansion (PWE) technique has been implemented in analysing the nature of the photonic bandgap (PBG) of the photonic structure which is a decisive factor for the calculation of output energy. The results are obtained by appraising the energy level of transmitted light through the photonic crystal structure.

Keywords: 2-D triangular photonic structure, Photonic bandgap, PWE technique,

1. INTRODUCTION

For envisaging sensing applications, temperature happens to be one of the promising parameters. Presently, the optical method is one of the popular methods to sense the temperature of the environment. To forbid direct contact, many domains of optical methods like photonic crystal structure, infrared pyrometers, resonators, fiber Bragg's grating, etc. are widely executed. Looking up to the potential applications, integrated photonics exihibit fore front uses in non-linear photonic devices in the domain of manufacturing technology, telecommunications, photovoltaics, biomedical engineering, solar cells, and other renewable and in many more frontiers [1-2]. For optical properties of the semiconductor materials, losses due to reflection, absorption, and transmission are also governed by temperature with reference to the wavelength of light used. Semiconductor Photonic crystal is extensively used for one of its important properties; photonic bandgap (PBG). The PBG is essentially a gap between the dielectric line and airline and can be expressed in terms of normalized frequency (ω) and propagation vector (k). The different dimensions of photonic crystals would contribute to the PBG depending on the wavelength of light used, refractive index, periodicity, direction, and the size of the crystal. Several methods are adapted to compute the PBG like the plane wave expansion (PWE) method, Korringa-Kohn-Rostoker (KKR) method, Finite element method (FEM) technique, Finite difference time domain (FDTD) method,etc.In [3-4],the PWE technique is implemented for the investigation of increase in hydrostatic pressure and rise in temperature in relation to the photonic crystal structure of 2D honeycomb lattice where GaAs crystal rods are immersed in the air [3] and triangular holes embedded in GaAs [4]. Implementing PWE also reveals the annular PCs have wider PBGs in comparison to air-hole PCs in [5]. PWE technique finds significant uses in the photonic structure to investigate the reflectance characteristics with the ranges of temperature and pressure variations. In the literature [6-11], the PWE technique is implemented for different 1-D and 2-D photonic structures by taking different light sources and semiconductor materials for sensing the temperature and pressure.In[6], four types of semiconductor materials are realized as the one-dimensional photonic structure to measure the temperature in the range of 102 to 390 K. Here, a one-dimensional grating structure is formed by using semiconductor material and air alternatively and the same structure is exposed by a light source of wavelength 10.59 µm. In [7], GaN waveguide is investigated to measure the temperature and pressure at the terahertz range where both reflection and absorption are considered for the computation of transmitted light energy. In this, the PWE technique is implemented for the calculation of reflected energy which exhibits an excellent linear relationship between input and output for both pressure and temperature.Similarly, polymer waveguide is implemented using the plane wave technique in [8] to measure the temperature in the range of 30°C to 80°C. In [9], Temperaturemeasurement is also realized by using Germanium and Silicon through different light in IR regime where absorption, reflection, polarization, and diffraction are taken into consideration to get the equivalent transmitted light energy. PWE technique is also applied to the one-dimensional photonic structure to get the reflectance characteristics.In [10] PWE method is implemented to investigate the temperature effect on the width of PBG in TE propagation mode at the wavelength 1.55 µm. Here both 2-D square and hexagonal photonic crystals are realized using an array of Silicon Carbide rods along with an air interface. Furthermore, a comparison of PBG has been made between SiC and Si photonic crystal, and quality factors are calculated via the FDTD method as well.PWE method is applied to a 2-D honeycomb photonic lattice to measure the temperature and pressure in [11] where PCS is composed of GaAs and air.

Considering the other methods for sensing temperature and pressure, in [12], 1-D photonic crystal structures are examined using the transfer matrix method to study the temperature and hydrostatic pressure effect. In this, PCS consists of GaAs and $Ga_{0.7}Al_{0.3}As$ as the grating structure in defect mode. The linear variation of reflectance with temperature has been studied in [13] with one-dimensional AlGaN photonic waveguide structure. A PCS based ring resonator is analyzed in [14] by MEEP to measure the temperature at the micron level where the change in refractive index is the key parameter that diverges according to the change in temperature.Using LN (Lithium Niobate) as the ultra-high sensitive sensor in [15], photonic crystal structures verify the increase of refractive index with a wide range of temperature.

Measurement of strain and temperature is experimentally demonstrated in [16] where fiber interferometers are used. A common mono-mode optical fiber is used along with a silicon-based PCS in [17] to develop a temperature sensor that can measure from 100 to 700degreescentigrade.The sensitivity of this sensor is higher in comparison with fiber grating sensors and it can be also used in harsh conditions**.** Sensing temperature and gas concentration using photonic crystals in [18] where sensitivity is manipulated by analyzing the shift in reflection peaks. An intimate temperature impact on photonic bandgap fiber is reported in [19] with a greater value of the refractive index, where the photonic bandgap plays an important role for temperature sensing. A Mach-ZehnderInterferometer using Silicon photonic sensor is proposed in [20] to sense the temperature where a LED is being taken as a light source.In [21], a low temperature sensor is proposed using 1-D dielectric photonic crystal where the dielectric-superconductor pair defect property has been investigated. A photonic crystal fiber and hollow-core fiber along with a composite interferometer is implemented in [22] to measure the temperature and refractive index.

In this work, four types of semiconductor materials are realized as the background material for the 2-D triangular photonic structure to measure the temperature in the range of 102K to 390K degree Kelvin using a constant light source of wavelength10.59 µm. To realize the same, the PWE simulation technique is implemented to obtain the reflectance characteristics which are varied according to the refractive index of the material at various temperature ranges. Finally, a comparative study is discussed regarding the linear characteristics between the temperature and the transmitted light energy by taking the different semiconductor materials as the background for PCS.

2. THE BASIC PRINCIPLE OF MEASUREMENT

The proposed idea for the measurement of temperature using photonic structure is based on the change in the refractive index of the semiconductor materials used in PCS due to the temperature deviation as shown in Table 1 [1]. When a constant light source is made to fall on the PCS, the PBG of the structure is varied depending upon the change in the refractive index of the background material. Here, the foremost intention is to measure the transmitted light energy being allowed to pass through the photonic structure which depends upon the refracted light energy due to the width of PBG.

Table 1: Refractive indices of different semiconductor materials w.r.t temperature at 10.59µm [1]

Refractive index of Si, Ge, InAs, InSb with respect to temperature (T) at wavelength 10.59 µm		
Semiconductor Materials	**Temperature, T(K)**	**Corresponding Refractive index**
Silicon (Si)	150	3.41
	200	3.412
	250	3.414
	300	3.416
	350	3.418
	390	3.42
Germanium	102	3.94

	150	3.95
	200	3.96
	250	3.97
	300	3.98
	350	3.99
	390	4
Indium arsenic (InAs)	102	3.435
	150	3.445
	250	3.47
	300	3.485
	350	3.5
	390	3.51
Indium antimonide (InSb)	102	3.832
	120	3.838
	140	3.847
	160	3.857
	180	3.867
	200	3.877
	220	3.887

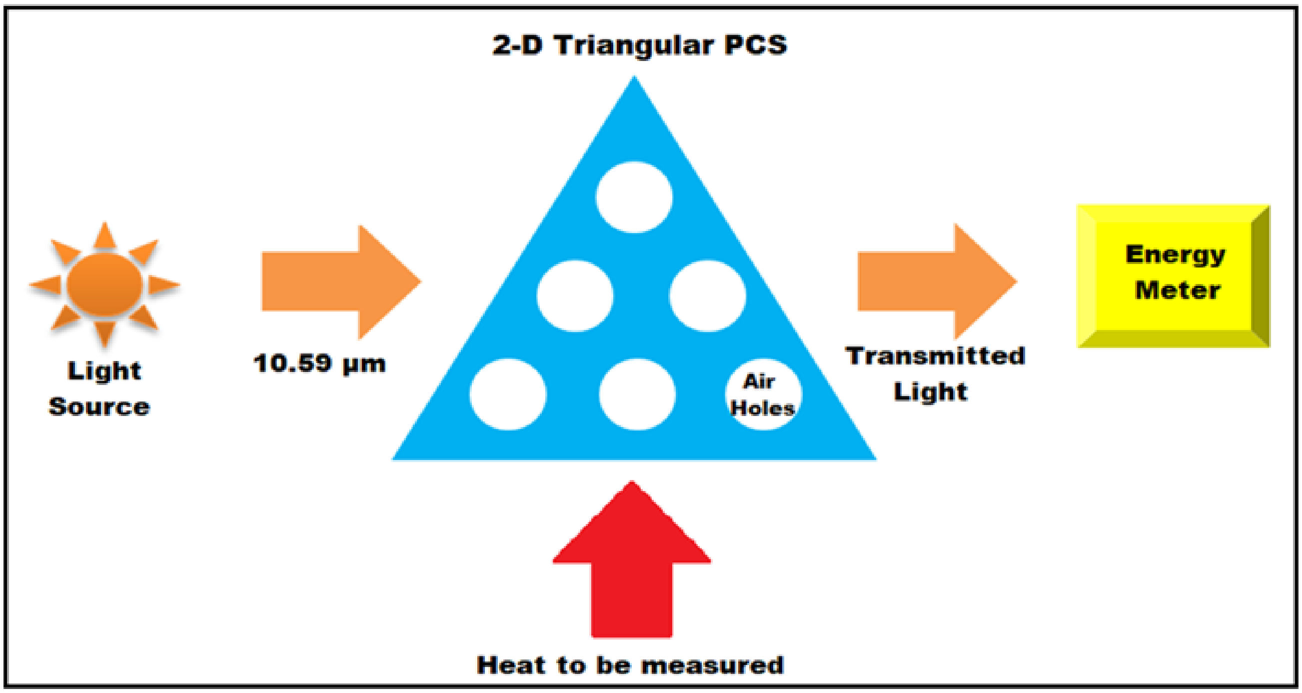

Fig. 1. Proposed setup for measurement

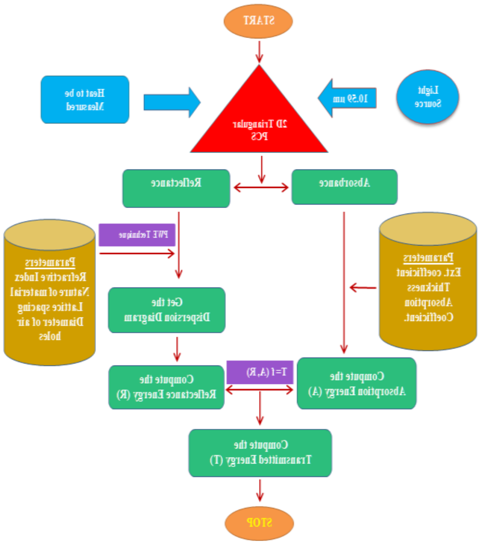

Fig. 2. The flow diagram of the proposed measurement principle

3. CALCULATION OF TRANSMITTED LIGHT ENERGY

For calculation of the transmitted light energy in terms of reflected light energy and absorbedlight energy, the following formula can be expressed

$$E_{tr} = (E_{in} - E_{re})e^{-(\alpha t+\beta d)} \qquad (1)$$

Where E_{tr}, $E_{in,}$and E_{re} represent the transmitted light energy, incident light energy, and reflected light energy respectively and $e^{-(\alpha t+\beta d)}$ is the efficiency factor related to the absorbed energy.

Again from the relation $E = \frac{hc}{\lambda}$ (where, h= Planck's constant, c = speed of light and λ= wavelength), incident light energy in terms of electron volt (eV) can be expressed as

$$E_{in} = \frac{1.24}{\lambda(\mu m)} \qquad (2)$$

By putting the value of the wavelength of incident light as 10.59 μm in the equation (2), we get

$$E_{inc} = \frac{1.24}{10.59} = 0.406779661 \quad \text{eV} \qquad (3)$$

Here, the incident light energy is constant throughout the calculation due to the fact that the same light source is considered for the photonic structure of different background materials.

Again the eq.(2) can be expressed as

$$E_{re} = 1.24 \times \frac{a}{\lambda} \qquad (4)$$

In the eq. (4), the term $\frac{a}{\lambda}$ is the normalized frequency related to the width of PBG which can be calculated by implementing the PWE technique. The different values of PBG is calculated for each type of PCS and temperature reading which is discussed in the next section.

Again from equation (1), the final equation is considered for this work is

$$E_{tr} = (E_{in} - E_{re}) \qquad (5)$$

In the above equation, the factor due to the absorption energy is not considered as the all the semiconductor materials exhibit negligible absorption at the source light wavelength of 10.59 μm.

4. SIMULATION RESULT AND DISCUSSION

As per the method discussed in the previous section, it is required to calculate the width of PBG to get the reflected light energy. So, the PWE simulation technique is realized separately for each type of semiconductor PCS by taking the appropriate radius of air holes and lattice constant. The radius of air holes is 0.35 μm for Silicon-based PCS and 0.4 μm for Germanium, InAs and InSb based PCS with lattice constant 1. Simulation is carried out for every corresponding refractive index on behalf of all semiconductor-based PCS as per the values specified in Table 1 to obtain the dispersion diagram. But, only two dispersion diagrams for each semiconductor-based PCSis shown in Fig.

3. In this figure, the red color bar represents the PBG with the corresponding width. Also in the dispersion diagram, X-axis signifies the wave vector (k) and Y-axis indicates the normalized frequency (a/λ).

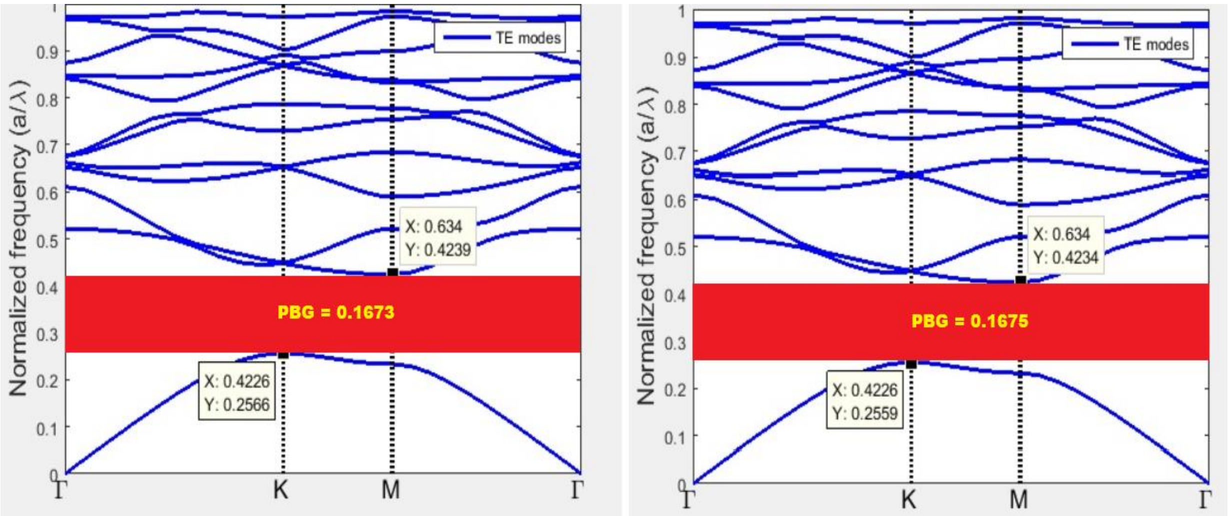

Fig. 3 (a) Dispersion diagram for Silicon-based PCS for the temperature of 150K and 390 K

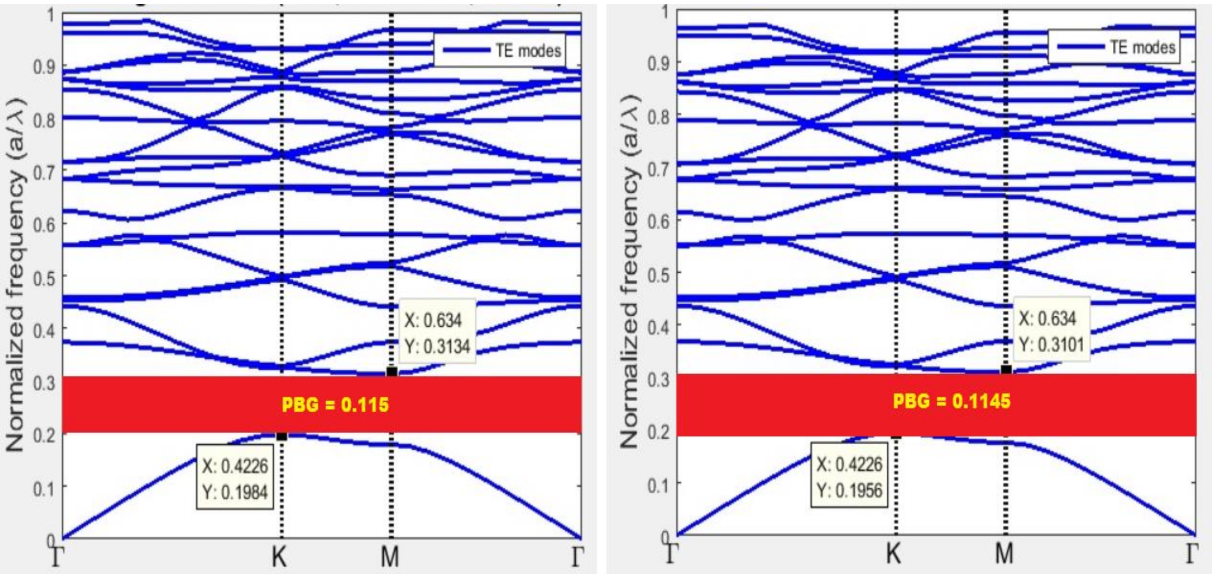

Fig. 3 (b) Dispersion diagram for Germanium based PCS for the temperature of 102K and 390 K

Fig. 3 (c) Dispersion diagram for InAs based PCS for the temperature of 102K and 390 K

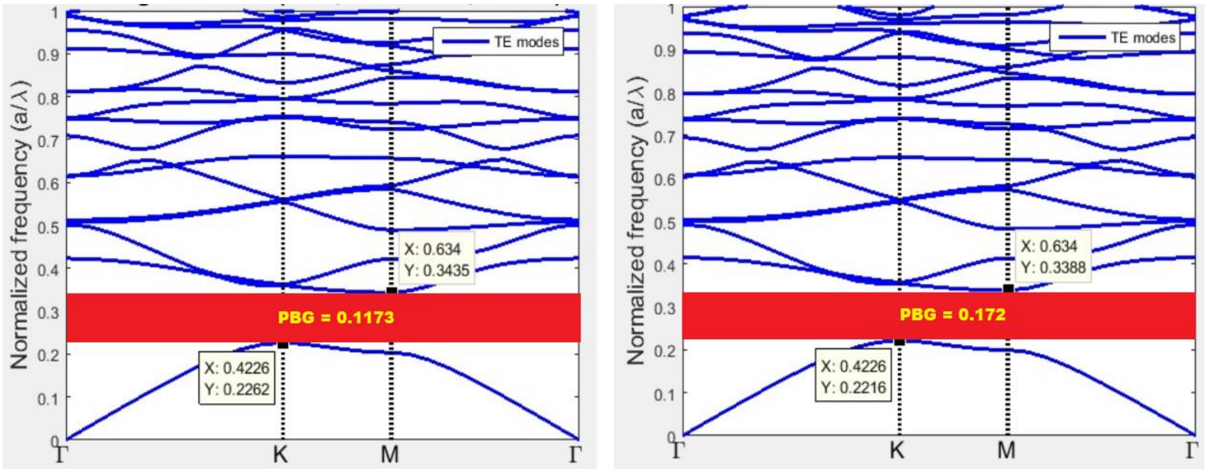

Fig. 3 (d) Dispersion diagram for InSb based PCS for the temperature of 102K and 220 K

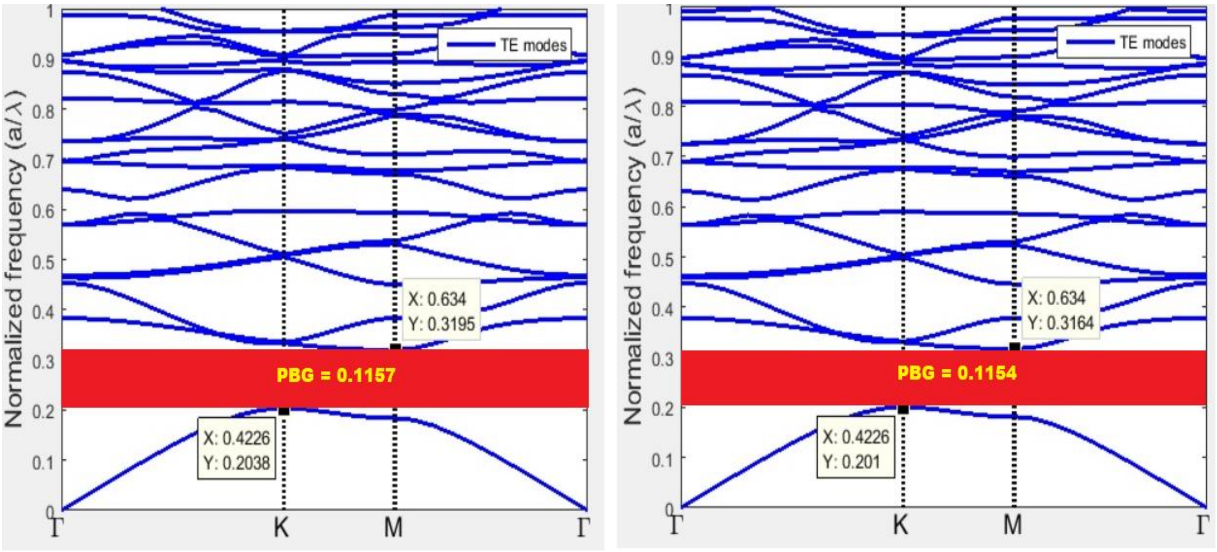

Fig. 3. Dispersion diagram of Si, Ge, InAs, InSb based photonic crystal for different temperature levels

The value of reflected light energy is calculated using the width of PBG from the dispersion diagram via eq.(4) and finally, the transmitted light energy is obtained by applying the final equation (eq.5) where the incident light energy is fixed at 0.406779661 eV. The complete value of PBG and transmitted light energy corresponding to the temperature and refractive index for each structure is given in Table. 2. The temperature variation of Silicon-based PCS ranges from 150 K to 390 K. Similarly, for Germanium and InAs based PCS the temperature ranges from 102 K to 390 K whereas, for InAs based PCS the temperature ranges from 102 K to 220 K. Pertaining to output, the transmitted light energy varies from [0.199079661 eV to 0.199327661 eV], [0.264179661 eV to 0.264799661 eV], [0.261327661 eV to 0.261327661 eV] and [0.263311661 eV to 0.263683661 eV] for Silicon, Germanium, InAs, InSb based PCS respectively. Interestingly, the transmitted light energy is decreasing with increasing value of temperature in Silicon-based PCS whereas for all other types of PCS the transmitted light energy is increasing with increasing value of temperature. The above elucidation is also represented in the corresponding graph which is shown in Fig. 4.

Table 2 (a) the relation of transmitted light energy and PBG w.r.t temperature where Ge and Si used as background material for 2-D triangular Photonic crystal

	Silicon as background material with radius of air hole 0.4 μm			**Germanium as background material with radius of air hole 0.35 μm**			
Temperature in K	**RI**	**PBG**	**Transmitted energy (eV)**	**Temperature in K**	**RI**	**PBG**	**Transmitted energy (eV)**
102	No data			102	3.94	0.115	0.264179661
150	3.41	0.1673	0.199327661	150	3.95	0.1149	0.264303661
200	3.412	0.1673	0.199327661	200	3.96	0.1148	0.264427661
250	3.414	0.1674	0.199203661	250	3.97	0.1147	0.264551661
300	3.416	0.1674	0.199203661	300	3.98	0.1147	0.264551661
350	3.418	0.1675	0.199079661	350	3.99	0.1146	0.264675661
390	3.42	0.1675	0.199079661	390	4.00	0.1145	0.264799661

Table 2 (b) the relation of transmitted light energy and PBG w.r.t temperature where InAs and InSb used as background material for 2-D triangular Photonic crystal

	Indium Arsenide(InAs) as background material with the radius of air hole 0.35 μm			**Indium antimonide (InSb) as background material with the radius of air hole 0.35 μm**			
Temperature in K	**RI**	**PBG**	**Transmitted energy (eV)**	**Temperature in K**	**RI**	**PBG**	**Transmitted energy (eV)**
102	3.435	0.1173	0.261327661	102	3.832	0.1157	0.263311661
150	3.445	0.1173	0.261327661	120	3.838	0.1156	0.263435661
200	3.47	0.1173	0.261327661	140	3.847	0.1156	0.263435661
250	3.485	0.1172	0.261451661	160	3.857	0.1156	0.263435661
300	3.5	0.1172	0.261451661	180	3.867	0.1155	0.263559661
350	3.51	0.1172	0.261451661	200	3.877	0.1154	0.263683661
390	3.435	0.1173	0.261327661	220	3.887	0.1154	0.263683661

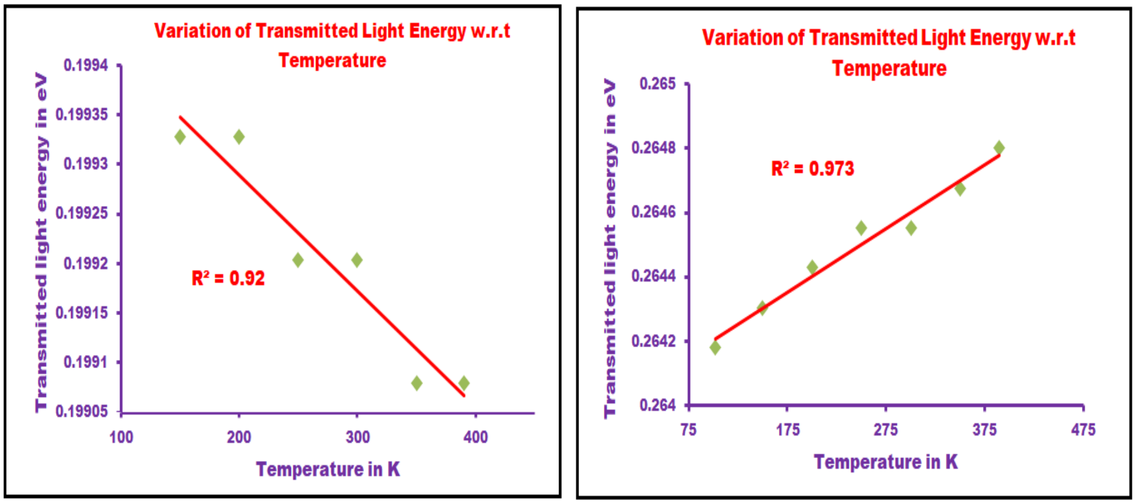

Fig. 4 (a) Silicon based PCS Fig. 4 (b) Germanium based PCS

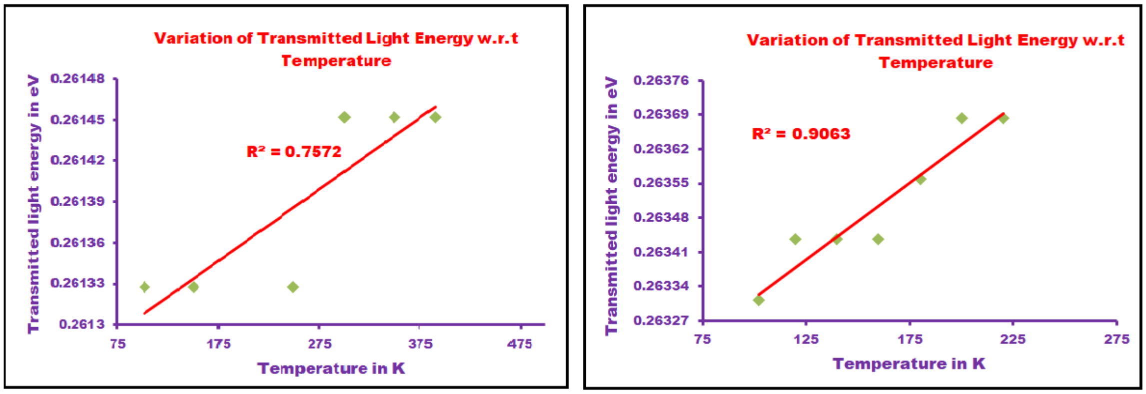

Fig. 4 (c) InAs based PCS Fig. 4 (d) InSb based PCS

Fig. 4. The plot between the temperature and the transmitted energy for Si, Ge, InAs, InSb based PCS

Simulation results visibly lead to trending linearity between the transmitted light energy and the temperature. Fig.4 depicts that the linearity scales above 90% in 2D triangular PCS of Si, Ge and InSb whereas it approaches 75% for InAs based 2D PCS. With a comparative analysis of linearity of all the four aforementioned semiconductor PCS for temperature measurement, the Ge based 2D triangular PCS comes out to be a suitably good candidate for the same as the linearity scales above 97% ($R^2 = 0.973$).

5. CONCLUSION

Four different semiconductor materials (Si, Ge, InAS, InSb) based 2-D triangular photonic structure are focused in this reserach to measure the temperature of the structres. PWE technique is implemented to investigate the reflectance characteristics of the photonic structure at 10.59 µm light source. Since zero absorption is accomplished with in all types of semiconductor-based photonic structure, the photonic band gap of the strucres controls the transmitted light energy which is coming out from the 2-D TPCS. A comparative studies is also made by considering the linearity curve among different type of semiconductor-based photonic crystals. Finally it is revealed that Germanium based photonic crystal structure could be a good candidate for the temperature measurement.

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