https://doi.org/10.53655/joe.e3462y

Jurnal OptoElektronik

High Sensitivity Temperature Sensor Based on Two-Dimensional Photonic Crystal

Sapna Dinodiya[1,3], B. Suthar[2] and A. Bhargava[3]

[1]*Department of Physics, Govt. Women Polytechnic College, Bikaner 334001, India*
[2]*Department of Physics, M.L.B. Govt. College, Nokha, Bikaner 334803, India*
[3]*Nanophysics Laboratory, Department of Physics, Govt. Dungar College, Bikaner 334001, India*
**Corresponding author*: sapnadinodiya@gmail.com

Keywords

Photonic Crystal
Pressure Sensor
Photonic Band Gap

Article History

Received: 02 April 2021
Accepted: 30 June 2021
Published: 15 July 2021

Abstract

In this work, a two-dimensional photonic crystal ring resonator based temperature sensor is investigated. The device consists of a hexagonal array of air holes surrounded by the base material of germanium (Ge). The sensing mechanism is based on the shifting of transmission peak with refractive index changes in Ge induced by variation of temperature. Simulation results are obtained using finite difference time domain method (FDTD). The photonic band gap is studied by plane wave expansion method (PWE). The sensor has sensitivity of 270 pm/K and quality factor of 2028.86 in the range of temperature detection between 300 K to 800 K. The size of the structure is 112.91 $(\mu m)^2$ and appropriate for sensing applications in nanotechnology. Temperature sensing is one of the important applications used in aerospace, defence, automobile, communication, medical science and in other fields. Temperature sensor based on photonic crystals are compact, highly sensitive, fast responsive and easy to be integrated. Compared with previous reported works our simulated sensor has the high sensitivity with good quality factor and compact size with wide range of temperature detection.

1. Introduction

Photonic crystals (PhCs) were first introduced by the work of Eli Yabnovitch [1] and Sajeev John in 1987 [2]. In past three decades, they have created special interest in research community of nanophotonics. Photonic crystal based devices are attributed by compactness, light weight and low power consumption. Performance of optical sensors can be enhanced by PhCs. They can detect accurately, respond rapidly and integrate easily into various platforms. PhC-based sensors have been developed in a wide range of sensing applications such as temperature [3]–[5], pressure [6]–[8], refractive index [9], magnetic fields [10], electric fields [11], chemicals [12]–[14] and biomolecules [15]–[17].

PhCs are periodic nanostructure with low and high refractive index materials. The periodic variation in structure produces a certain ranges of frequencies where propagation of light is totally restricted. This forbidden frequency region is named as photonic band gap (PBG) [18]. By introducing defects in the structure, light can be confined in photonic band gaps. The confinement of light can be further controlled by external parameters and this phenomenon is exploited in sensors. In 1D PhCs, defects are created by asymmetry in layered structure but in 2D, defects are formed by micro cavities, waveguides [19], [20] and ring resonators [21].

Temperature sensing is one of the important applications in medical, communication, aerospace, and in other numerous fields. Thermo-optical properties of materials in 1D and 2D PhCs can be used efficiently in temperature sensing. Recently, several 2D PhC-based temperature sensors were designed and attempts were made to improve their performance [22]–[24].

The purpose of this study is to simulate a ultra-compact 2D PhC ring resonator (PhCRR) based temperature sensor of high sensitivity. The choice of the 2D PhCRR structure is decided for providing better quality factor and clear transmission peak that shifts in wide dynamic range. The shifting of band gaps with temperature is observed more pronounced with germanium (Ge) in comparison to the other semiconductors like Si and ZnO [25]. Therefore, Ge is used to achieve high sensitivity.

2. Theoretical Model of PhC

The basic structure of temperature sensor consists of hexagonal lattice of air holes in Ge matrix with refractive index of 4.39. The number of air holes in X and Z directions are 31×31. The radius of air holes is 0.37 a, where lattice constant a is taken as 355 nm which is the distance between centres of two adjacent air holes The length and width of structure is 11.36 μm and 9.94 μm respectively, i.e., the total size of structure is 112.91 $(\mu m)^2$. The lattice constant and radius of circular hole have been chosen to maximise photonic bandgap around the reference wavelength of 1550 nm. In this lattice, a ring resonator is created coupled with inline quasiwaveguide that produces a narrow peak in the transmission spectrum that is used to detect the temperature. The incident source is a Gauss impulse light source located at the input of the waveguide and the detector is placed at the end of the waveguide.

3. Method and Materials

The PWE (Plane Wave Expansion) method is used to obtain the PBG of regular structure. It is a computational technique to solve Maxwells equations by formulating a eigen value problem. The periodic functions are expanded in terms of Fourier series components and used in wave equation that can be simplified into eigen value relations. Eigen value relations can be solved in dispersion relation between frequency of the modes and wave vector usually plotted in the form of band diagram [26].

Transverse-magnetic (TM) mode is considered for sensor design. The band diagram of structure is illustrated in Figure 1. There is one PBG whose normalized frequencies lie between 0.1859 a/λ and 0.3234 a/λ. The corresponding wavelength range is between 1097.71 nm and 1909.62 nm.

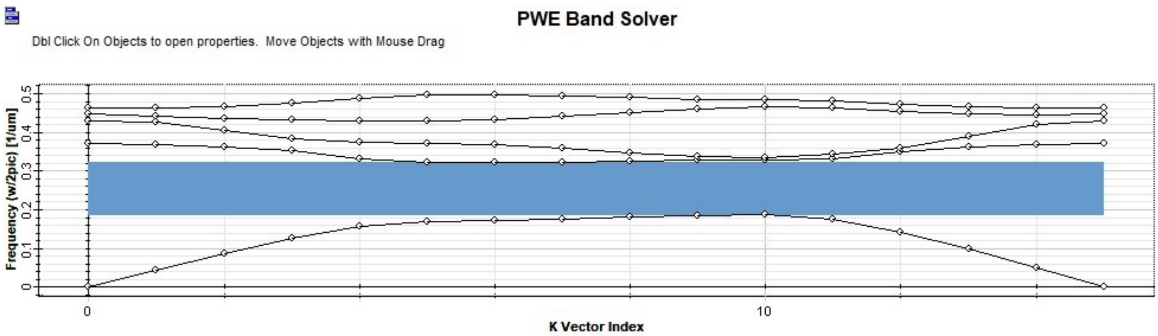

Figure 1. Structure of TM mode band gap

To induce the localisation of light in PBG, a ring resonator (adjoint with two waveguides) is created in aforesaid PhCs structure. Simulated sensor design is shown in Figure 2.

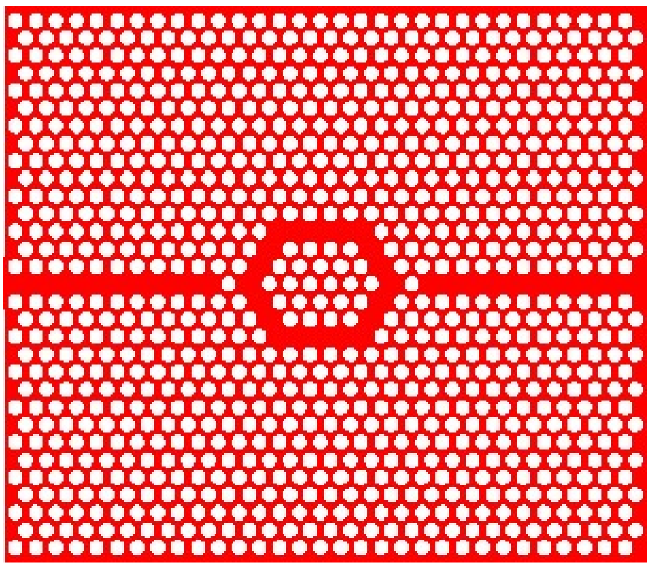

Figure 2. Schematic diagram of PhC based sensor

 https://doi.org/10.53655/joe.e3462y

In this work, performance of temperature sensor is studied by finite-difference time domain (FDTD) method [27]. FDTD is a numerical method in which time dependent Maxwell's equation in partial differential form is discretized using central approximations to the space and time. It can be employed for calculation of the transmission spectrum due to the propagation of electromagnetic fields. We have used computational domain of 31×31 lattice constants (total 961 unit cells). The computation domain is surrounded by PML (perfectly matched layers). The total number of time steps is taken 250,000 with each time step $\Delta t = 0.99/c\sqrt{\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}}$, where c is the speed of light, Δx and Δy are space intervals.

A Gaussian beam by incident source is applied at the input waveguide and get interacted with the ring resonator. Output waves are detected by the monitor placed at the output waveguide. The sensing mechanism of temperature sensor is based on thermo-optic effect. In this effect refractive index of the medium vary with temperature. By increasing the temperature of the sensor, refractive index of Ge slab can be increased, which leads to modifying the PBG and subsequent shifting of resonant wavelength.

The refractive index (n) of Ge in the range 1200 – 14000 nm and 293–800 K can be expressed as a function of both the wavelength and temperature as [28]:

$$n^2(\lambda, T) = \varepsilon(T) + \frac{e^{-\frac{3\Delta L(T)}{L293}}}{\lambda^2} \times (2.5381 + 1.8260\times10^{-3}T + 2.8888\times10^{-6}T^2) \quad (1)$$

where the dielectric constant equals:

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

and thermal expansion equals:

$$\frac{\Delta L(T)}{L293} = 5.790\times10^{-5}(T-293) + 1.768\times10^{-9}(T-293)^2 - 4.562\times10^{-13}(T-293)^3 \; for\, 293K \le T \le 800K \quad (3)$$

4. Results and Discussion

A temperature sensor based on, ring resonator structure is proposed as a configuration of air holes in Ge slab. When the beam of light is passed through the ring resonator from input waveguide, then it is intensed over multiple round-trips for few particular wavelengths because of constructive interference. Therefore ring resonator in PhCs works as an optical filter. Transmitted light at the output can be controlled by size of airholes or material refractive index. The size of air holes is optimised for better performance indexes. The normalized transmission characteristics are obtained by FDTD method. The temperature of the structure is varied from 300 to 800 K with an increment of 100 K. The refractive index of Ge increases with temperature as shown in Figure 3.

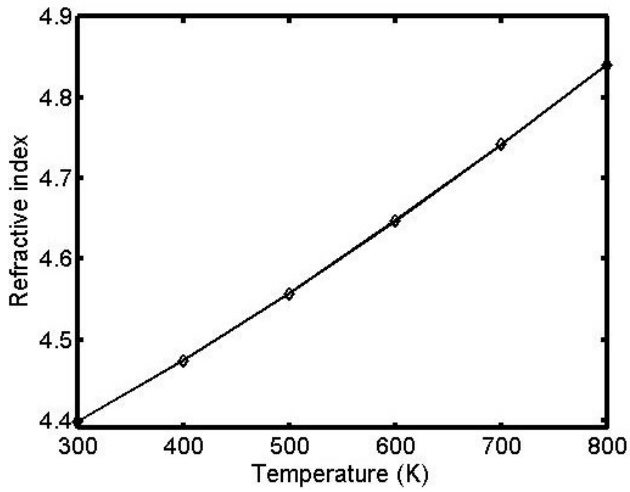

Figure 3. The variation of refractive index with temperature

The normalized transmission spectrum is shown in Figure 4. In transmission curves, a resonance peak is observed at 1406 nm ($T = 300K$) in photonic band gap. The transmitted power remains constant as the temperature increases but the change in wavelength of transmission peak is observed even with the slight change in temperature. It can be seen, the resonant wavelength mode shifts to higher wavelengths (red-shift) with temperature.

Sensitivity is an important parameter to indicate the performance of a sensor and in case of temperature sensor, it is defined by the ratio between the shift of resonant wavelength ($\Delta\lambda$) and the temperature change (ΔT). It is written as [22]:

$$S_T = \frac{\Delta\lambda}{\Delta T} \tag{4}$$

Mostly, the sensitivity of a temperature sensor is expressed in units of $pm/°C$ or pm/K.

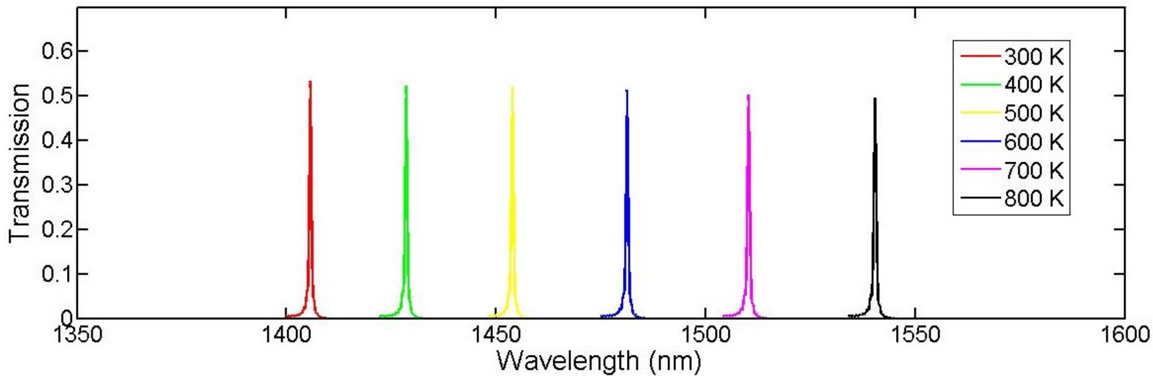

Figure 4. Normalised transmission spectrum of sensor

The parameters such as refractive index, resonant wavelength, quality factor and detection limit are affected by variation in temperature. Table 1 summarizes the results obtained for the structure.

Table 1. Variation of simulation parameters with temperature

Temperature	Refractive Index	Resonant Wavelength (nm)	Quality Factor	Detection Limit (K)
300K	4.3989	1406	2028.86	/
400K	4.4740	1429	1990.25	0.312
500K	4.5572	1454	1986.61	0.292
600K	4.6468	1481	1961.32	0.279
700K	4.7417	1510	1923.07	0.270
800K	4.8403	1541	1887.48	0.263

A total shift of $\Delta\lambda = 135nm$ is observed in temperature range 300 to 800 K. The maximum value of quality factor is 2028.86. The values of refractive index at temperatures 300 K and 800 K are 4.3989 and 4.8403, respectively. In this case, the refractive index sensitivity is equal to 305.84 nm/RIU.

Sensor efficiency is also described by detection limit (DL) which is the smallest value of the change of temperature that can be detected by the sensor. DL can be expressed as [29]

$$DL = \frac{\lambda}{10SQ} \tag{5}$$

λ is resonant wavelength, S and Q are sensitivity and quality factor respectively. Smallest DL is required to design a good sensor. In this simulation, we find minimum value of DL as 0.263 K.

A curve between the resonant wavelength and the temperature is shown in Figure 5. It is obvious from the figure that resonant peak varies with respect to the temperature in the same way as refractive index changes with temperature. The sensitivity of the device is estimated from the curve and it is found to be 27 $nm/100K$ or 270 pm/K. This sensor can work in a temperature range from 300 K to 800 K.

Table 2 provides the comparison of our work with previously reported results in the literature. In compare to other PhCs based temperature sensor [22]–[24], our simulated sensor has the highest sensitivity with good quality factor and has a wide range of temperature detection with compact size of the structure.

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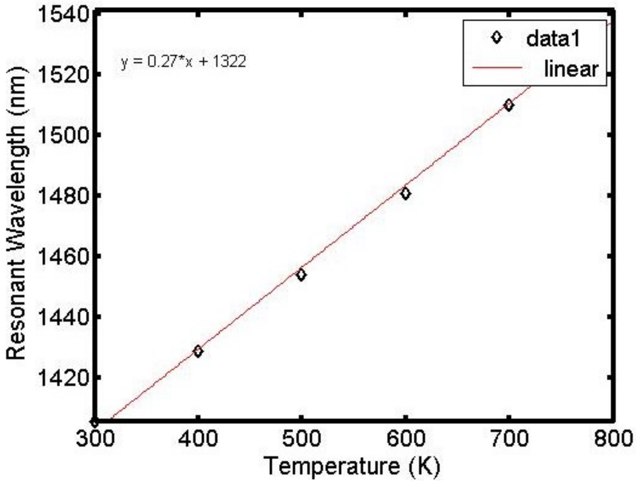

Figure 5. The variation of resonant wavelength with temperature

Table 2. Comparison of results with previous work

Reference	Year	Dynamic Range	Quality Factor	Sensitivity (pm/K)	Size (μm^2)
Rajasekar et al.	2018	$278K$ to $815K$	738.7	59.25	217.12
Zegadi et al.	2019	$273K$ to $633K$	**	92.3	114.08
Bounaas et al.	2020	$273K$ to $353K$	2506.5	93.61	115.42
This work		$300K$ to $800K$	2028.86	270	112.91

5. Conclusion

An ultra-compact 2D PhCRR temperature sensor is proposed. The ring resonator is coupled with inline quasi-waveguide which produces a narrow peak in the transmission spectrum that is used to detect the temperature. Proposed temperature sensor presents a maximum quality factor of 2028.86 and the sensitivity of 270 pm/K in temperature range 300 to 800 K. Detection limit of the sensor is about 0.26 K .The refractive index sensitivity of the proposed sensor is about 305.84 nm/RIU. Our presented design provides high sensitivity compared with some recent works. The total chip area of the proposed sensor is 112.91 $(\mu m)^2$. Hence, it is suitable for the integrated optics and nanotechnology.

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