High Resolution Nano Temperature Sensor based on Two-Dimensional Photonic Crystal

Pardis Kazemi Esfeh[1], Zahra Alaei[2*]
1- Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran.
Email: kazemipardis@gmail.com
2- Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran.
Email: alaie.zahra@yahoo.com (Corresponding author)

Received: July 2019 Revised: September 2019 Accepted: November 2019

ABSTRACT:
In this paper, we designed a two-dimensional photonic crystal measurement nano-sensor with an octagonal ring resonator. This nano-sensor is designed using circular silicon rods in a rectangular lattice with a lattice constant of 820 nm, to detect temperatures from 0 ° C to 540 ° C. Photonic band gap was calculated by PWE method and the sensor operating parameters such as sensitivity, transmission efficiency, and quality factor were calculated by FDTD method. As the temperature increases, the resonance wavelength changes to a higher wavelength. The designed photonic crystal nano-sensor works at the resonance wavelength λ = 1733 nm and with the TE polarization. The maximum transmission efficiency, quality factor, and sensitivity are 100%, 582.66, and 33.33 pm/°C, respectively. This nano temperature sensor, designed to work in the nanoscale, can sense the slightest temperature change, so it is well suited for critical and sensitive nanotechnology systems.

KEYWORDS: Photonic Crystal Sensor, Temperature Sensor, PWE, Transmission Efficiency.

1. INTRODUCTION

Generic sensors used in various industries have limitations in sensitivity, measurement range, and data transfer capability. Due to the development of more complex industries requiring higher accuracy and performance than sensors, research on photonic crystal sensors has been expanded as a viable alternative. Photonic crystal sensors have advantages such as low loss, high speed, high power, and small dimensions. In the recent years, design of these types of sensors has received increasing attention.

For the first time in 1987, the concept of photonic crystals was independently proposed by Yablonovitch [1] and John [2] After predicting the feasibility of complete band gap structures in 1987, with the development of observation and measurement tools, it was found that natural photonic crystals appeared in many natural materials [3].

Photonic crystals are nano-structure with different dielectric materials that are arranged in a periodic structure to control the electromagnetic wave within the structure [4]. One of the most important properties of photonic crystals is the property of confining and controlling light. These properties allow photonic crystals to be used in various sensing systems [4].

A sensor is a device that senses and analyzes physical and biological parameters and responds accordingly. So far, a lot of various electronic sensors were designed, but these sensors have limitations, that these limitations are reduced or destroyed by optical sensors. Some optical sensors can be designed using photonic crystals [5].

Optical sensors have been effectively used in many applications to measure various parameters such as pressure, temperature, rotation, refractive index, flow and chemical gas [6]. Temperature measurement is widely used in various industries including petrochemical industry risk control and industrial safety, so it is very important [4], [7], [8].

FU Hai-Wei *et al.* in 2011 proposed a sensor based on photonic crystal microcavity and waveguide to measure temperatures from 0 ° C to 100 ° C. The temperature sensitivity of their proposed sensor was 6.6 pm/° C [9]. In 2014 Boruah *et al.* reported a sensor based on a photonic crystal cavity for temperature measurement from 25 ° C to 200 ° C and a maximum quality factor of 214 [10]. In 2015, Malika *et al.* reported a photonic crystal ring resonator based sensor for the detection of temperature change at micron level. They found that the wavelength value varied when exerting an external effect on the entire structure [11].

In the following section, in the second section will be discussed, the method of measuring the temperature photonic crystal sensor. In the third section, we will design the structure of a nano-temperature sensor based on an octagonal photonic crystal ring resonator with plane wave expansion (PWE) and finite-difference time-domain (FDTD) method. Finally, we conclude the article with the conclusion section.

2. SENSING PRINCIPLES OF PHOTONIC CRYSTAL TEMPERATURE SENSOR

The sensing temperature method is based on refractive index variations via thermo-optical effects. As the temperature of the sensor increases, the refractive index will change, causing the photonic band gap and the wavelength of the photonic crystal structure to change. Usually, the relation between the refractive index and temperature is defined as follows [12]:

$$n = n_0 + \alpha\, \Delta T \qquad (1)$$

In the above relation, n_0 is the refractive index at 0 °C (n_0 = 3.42), α is the thermo-optical coefficient, which is 2.4×10^{-4}/° C for silicon [13], and ΔT is the temperature difference. As the temperature increases, the refractive index of silicon increases [4].

Usually, there are two sensing mechanisms for optical sensing, the resonance wavelength variation scheme and the intensity variation scheme. The sensitivity of this resonance wavelength scheme is better than the other one [14], [15].

3. DESIGN OF PHOTONIC CRYSTAL TEMPERATURE SENSOR STRUCTURE AND ANALYSIS OF PHOTONIC BAND GAP

The temperature sensor proposed in this paper is based on two-dimensional photonic crystals enclosed in a rectangular lattice of circular dielectric rods surrounded by air with a refractive index of n = 1.

According to Fig. 1. The number of rods in the complete photonic crystal structure without defects in the X and Z directions is 25 and 19, respectively. The radius of the rods is r = 240 nm and the lattice constant is a =820 nm. The rods are made of silicon and their refractive index is n = 3.42, as shown in Fig. 2.

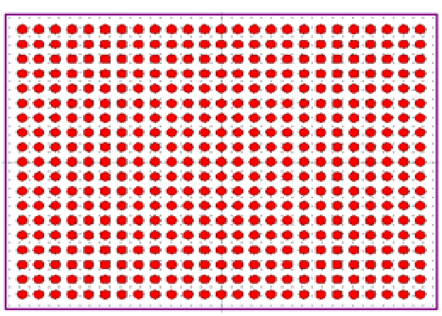

Fig. 1. Structure of temperature photonic crystal sensor, without defects.

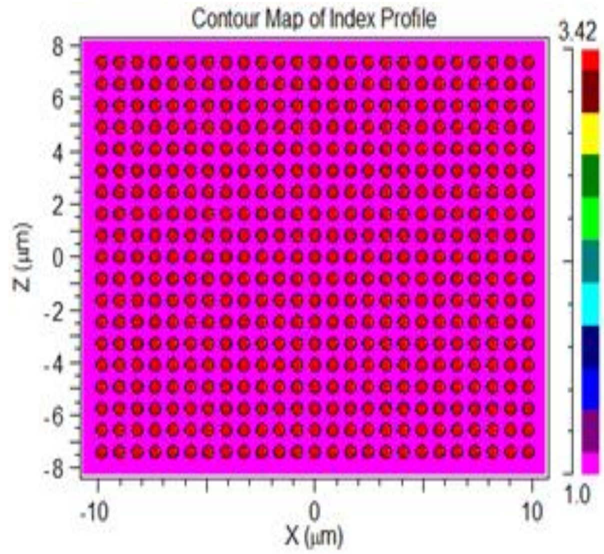

Fig. 2. The refractive index of the structure.

Using PWE numerical method in Rsoft software and BandSOLVE module the photonic band gap and emission modes are obtained. Therefore, suitable values can be obtained for designing a nano-temperature sensor.

In the band structure of this proposed sensor, there are three TE band gaps, as shown in Fig. 3. In this diagram, the vertical and horizontal vectors represent the frequency vector and the wave vector, respectively.

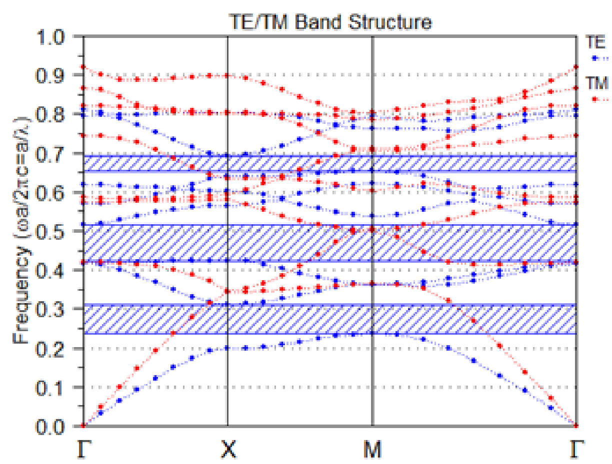

Fig. 3. Structure of temperature photonic crystal sensor, without defects.

The values of the photonic band gap are given in detail in Table 1, which we use in this paper as the second photonic band gap in the wavelength range 1589 nm to 1938 nm, which corresponds to the third optical window. It is suitable for sensor design.

Table 1. Frequency and wavelength band structure of the proposed temperature sensor.

Photonic Band Gap	Frequency (a/λ)	Wavelength (λ) (nm)
PBG 1: TE	0.654 – 0.691	1186 - 1253
PBG 1: TE	0.423 – 0.516	1589 - 1938
PBG 1: TE	0.237 – 0.312	2628 - 3459

Fig. 4. shows the proposed temperature sensor, which created by linear and point defects, an octagonal ring resonator and two quasi-waveguides in the rectangular lattice. The radius of the inner rod of the octagonal ring resonator (Blue rods) is R_c = 128 nm.

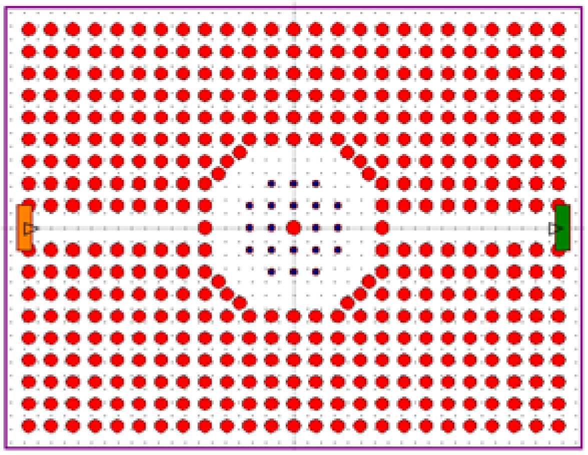

Fig. 4. Schematic diagram of the photonic crystal nano-temperature sensor based on octagonal ring resonator in rectangular lattice.

By creating defects in the sensor substrate, guided modes in the band gap occur. According to Fig. 5 except a part of the band gap with frequency between 0.488 a/λ to 0.494 a/ λ and wavelengths between 1660 nm to 1680 nm, all other parts are guided modes.

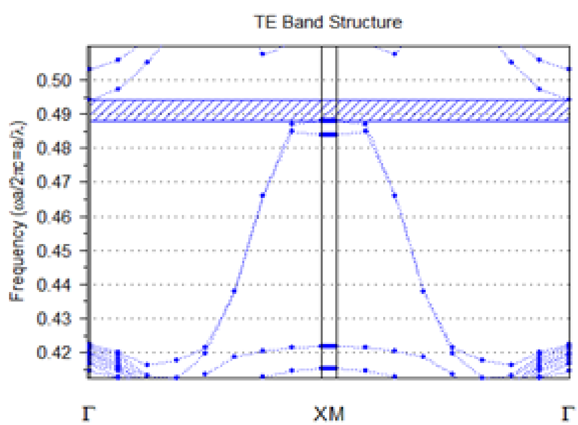

Fig. 5. Guided modes created in the temperature sensor band gap.

By analyzing the guided modes, we conclude that frequency of 0.473 a/ λ and wavelength of 1733 nm the light signals are strongly confined inside the octagonal ring resonator, and can produce the best quality factor. Give us. The three-dimensional schematic of the proposed temperature sensor structure with a size of 16.4 µm × 21.4 µm is also shown in Fig. 6.

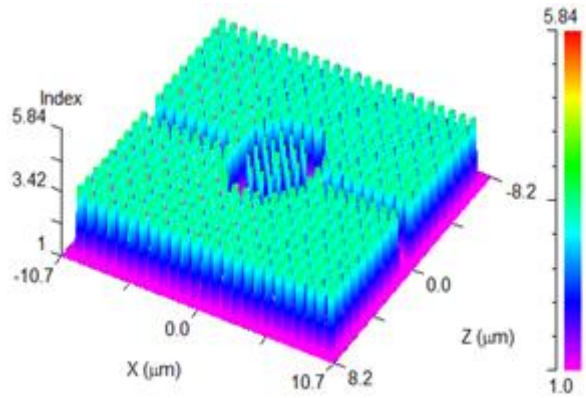

Fig. 6. Three-dimensional schematic of structure.

4. SIMULATION AND ANALYSIS OF PHOTONIC CRYSTAL TEMPERATURE SENSOR PARAMETERS

Sensing temperature in photonic crystal structures is based on refractive index changes, when the temperature changes, the refractive index changes as well as the resonant wavelength changes. So, with that in mind, we will notice a change in temperature.

Using the FDTD method and the Fullwave module, the normalized output spectrum of the photonic crystal octagonal ring resonator, without applying temperature (0 °C) is shown in Fig. 7. where the resonance wavelength, transmission efficiency, and quality factor are 1733 nm, 100%, and 403.24, respectively. The electric field distribution of the proposed nano-temperature sensor at ON and OFF resonance is also shown in Fig. 8(a) and Fig. 8(b), respectively.

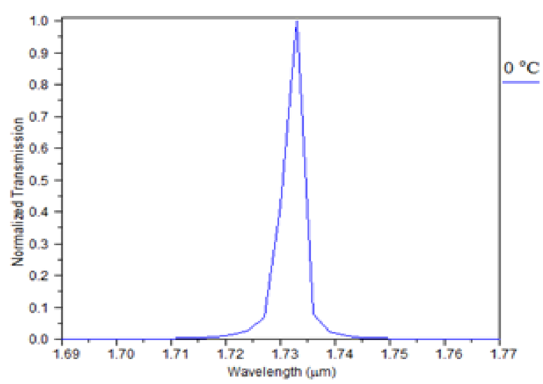

Fig. 7. Normalized output spectrum of proposed temperature sensor without applying temperature.

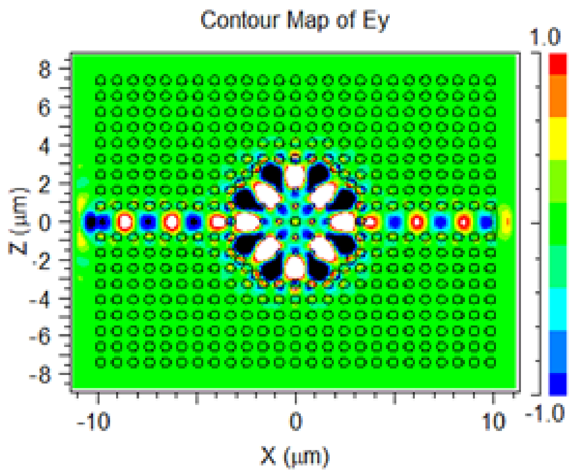

Fig. 8(a). Electric field distribution of proposed temperature sensor at ON of 1733 nm.

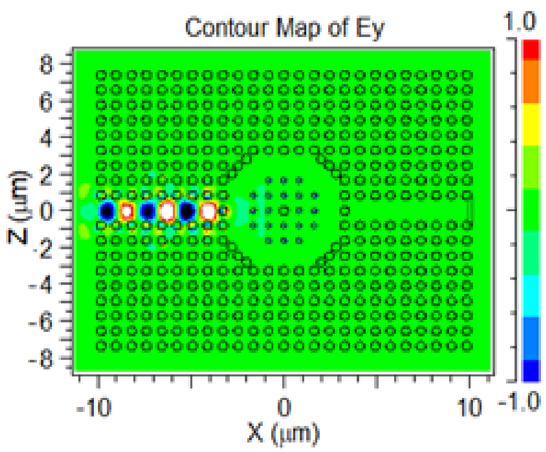

Fig. 8(b). Electric field distribution of proposed temperature sensor at OFF of 1670 nm.

To analyze the effect of temperature on the designed sensor, we perform simulations at different temperatures from 0 ° C to 540 ° C. The diagrams of the different temperatures are shown in Fig. 9. It is observed that as the refractive index increases, the resonance wavelength changes and is transferred to a region of higher wavelengths.

The resonance wavelength, transmission efficiency, quality factor, and sensitivity of the designed temperature sensor at different temperature levels are given in Table 2, the maximum transmission efficiency, quality factor, and sensitivity are 100%, 582.66, and 33.33 pm/°C, respectively. The temperature sensitivity value of the sensor is obtained through the following relation:

$$S_T = \frac{\Delta\lambda}{\Delta T} \quad (2)$$

Where ΔT is the temperature difference and Δλ is the resonance wavelength difference.

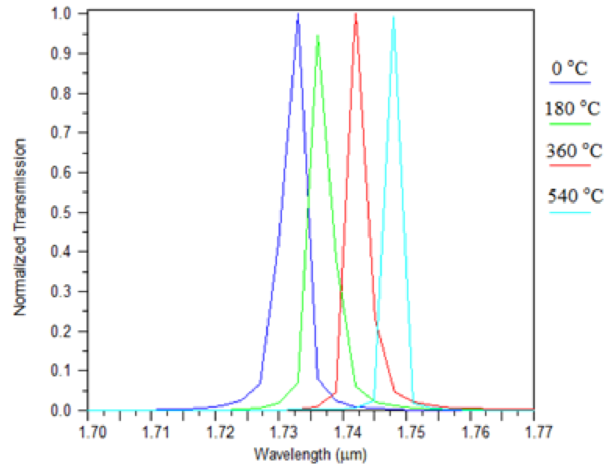

Fig. 9. Normalized output resonance spectrum for temperatures ranging from 0 ° C to 540 ° C.

Table 2. Operating parameters of the sensor at different temperature levels.

Level of Temperature (°C)	Refractive index (RIU)	Resonant wavelength (nm)	Quality factor	Transmission efficiency (%)	Temperature sensitivity (pm/°C)
0	3.42	1733	403.24	100	……..
180	3.4632	1736	445.12	94	16.66
360	3.5064	1742	470.81	100	33.33
540	3.5496	1748	582.66	99	33.33

In Table 3, the comparison between this work and the previous works is presented in the following table. According to the table, we find that the proposed nano temperature sensor in this paper performs well.

Table 3. Comparison of temperature sensor parameters between this article and previous articles.

References from previous articles	Range of Temperature (°C)	Quality factor	Transmission efficiency (%)	Temperature sensitivity (pm/°C)
[9]	0 - 100	…	…	6.6
[16]	5 - 25	477.83	99.5	…
[10]	25 - 200	214	…	…
This article	0 - 540	582.66	100	33.33

5. CONCLUSION

We designed a photonic crystal sensor based on an octagonal ring resonator for measuring temperatures from 0 ° C to 540 ° C. We used the PWE method to derive the guided mode at different temperature levels and the FDTD method to investigate the proposed operating parameters of the structure. Sensor performance is in the wavelength range of 1589 nm to 1938 nm and its resonance wavelength is 1733 nm. The refractive index of sensor changes as the temperature increases, and resulting in a change in the resonance wavelength.

According to the results obtained from the simulation, the maximum quality factor and sensitivity are 582.66, and 33.33 pm/° C, respectively. The size of the designed structure is 16.4 µm × 21.4 µm, which is compact, hence suitable for optical integrated circuits and nano-opto-electro-mechanical systems.

REFERENCES

[1] E. Yablonovitch, **"Inhibited spontaneous emission in solid-state physics and electronics"**, *Phys. Rev. Lett*. 58, 2059, 1987.

[2] S. John, **"Strong localization of photons in certain disordered dielectric superlattices"**, *Phys. Rev. Lett*. 58, 2486, 1987.

[3] E. Yablonovitch, T. J. Gmitter, **"Photonic Band Structure: The Face-Centered-Cubic Case,"** *J. Optical Society American A*, No. 9, Sept. 1990.

[4] R. Rajasekar, S. Robinson, **"Nano-Pressure and Temperature Sensor Based on Hexagonal Photonic Crystal Ring Resonator,"** *Plasmonics*. 14. 1-13. 2018.

[5] T. Dharchana, A. Sivanantharaja, S. Selvendran, **"Design of Pressure Sensor Using 2D Photonic Crystal,"**. *Advances in Natural and Applied Sciences.* pp. 26-30, 2017.

[6] L. Zhang, J. Lou, L. Tong, **"Micro/nanofiber optical sensors,"** *Photon Sens*. pp, 31-42, 2011.

[7] Y. Zhang, J. Huang, X. Lan, L. Yuan, H. Xiao, "**Simultaneous measurement of temperature and pressure with cascaded extrinsic Fabry-Perot interferometer and intrinsic Fabry-Perot interferometer sensors**,". *Optical Engineering.* No.7, 2014.

[8] H. Xu, M. Hafezi, J. Fan, JM. Taylor, GF. Strouse, Z. Ahmed, "**Ultra-sensitive chip-based photonic temperature sensor using ring resonator structures**,". *Optics Express*. pp, 3098-3104, 2014.

[9] Fu H-w, H. Zhao, X-g. Qiao, Y. Li, D-z. Zhao, Z. Yong, **"Study on a novel photonic crystal temperature sensor,"**. *Optoelectron Letters*. pp, 419-422, 2011.

[10] J. Boruah, Y. Kalra, RK. Sinha, "**Demonstration of temperature resilient properties of 2D silicon carbide photonic crystal structures and cavity modes**,". *Optik*. pp, 1663-1666, 2014.

[11] C.S. Mallikaa, I. Bahaddura, P.C. Srikantha, P. Sharan, "**Photonic crystal ring resonator structure for temperature measurement**,". *Optik*. pp, 2252-2255, 2015.

[12] M. Huang, **"Stress effects on the performance of optical waveguides,"** *Int J Solids Struct*. pp, 1615–1632. 2003.

[13] K.V. Shanthi, S. Robinson, **"Two-dimensional photonic crystal based sensor for pressure sensing,"** *Photon Sens*. pp, 248-253. 2014.

[14] R. Arunkumar, T. Suganya, S. Robinson, **"Design and analysis of photonic crystal elliptical ring resonator based pressure sensor,"** *Int J Photon Opt Technol.* pp, 30–33. 2017.

C. Y. Chao, L. J. Guo, **"Design and optimization of micro ring resonators in biochemical sensing applications,"** *IEEE J. of Lightwave Technology*, pp, 1395-1402. 2006.

[15] S. Robinson, R. Nakkeeran, **"PC based optical salinity sensor for different temperatures,"** *Photon Sens*, pp, 187–192. 2012.