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High Sensitivity Temperature Sensor Based on Photonic Crystal Resonant Cavity

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Abstract—In this paper we investigate a new design of high sensitivity photonic crystal temperature sensor (PCTS). A square lattice of silicon (Si) rods immersed in air matrix is used as a basic structure. The designed sensor consists of two inline quasi-waveguides which are coupled to a resonant cavity (RC). The sensing principle is based on Si refractive index change caused by the variation of the temperatures over a range from 0 to 80°C. This variation leads to an important shift in the resonance wavelength. The performance of the suggested temperature sensor has been analyzed and studied using finite-difference time domain (FDTD) method. The results show that our designed structure offers a high sensibility of 93, 61 pm/°C and quality factor of 2506.5. Its structure is very compact with total size 115.422 μm^2, which is suitable for nanotechnology based sensing applications.

1. INTRODUCTION

Many efforts have been made to make nano-scale devices such as optical sensors because they are promising candidates for photonic integrated circuits (PIC). Due to the importance of these components and their distinct advantages, such as smallness, low power, light weight, precise detection, and rapid response, they have received much attention in the scientific community. Refractive index (RI) based optical nano-sensors have gained enormous interest due to their wide range of applications for sensing diverse parameters. Photonic crystals (PhCs) offer a promising prospect for the realization of optical sensor with ultra-low optical loss, which leads to a confinement of light within the sample. These artificial structures are periodic material whose dielectric permittivity is modulated periodically on one, two, or three directions in space [1]. This periodic variation produces a wavelength region where the light wave is totally reflected for both polarizations and all directions of the propagation. This forbidden frequency region is called photonic band gap (PBG). Several attempts have been made recently to design PhC-based sensors to detect medical diagnostics [2–5], chemical gas [6–8], refractive index detection [9], pressure [10–13], etc.

The scope of this paper is to propose and simulate an ultra-small optical sensor for detecting temperature variation. In the literature, different designs have been proposed [13–18]. Our suggested device is formed by combination of two inline quasi-waveguides and a resonant cavity. Its detecting principle is based on Si refractive index change caused by the variation of the temperatures over a range from 0 to 80°C, leading to variation in its peak wavelength. In order to obtain high sensibility and quality factor, two techniques are used. The first technique is to etch eight silicon particles situated around the resonant cavity, in order to get eight core/shell (C/S) rods. The obtained C/S rods consist of an outer Si layer called the shell concentrically surrounding the inner hole named the core. Among these rods, four of them have been shifted horizontally and vertically with a distance d equal to 0.2 µm. The second technique is to add and adjust some additional rods between the C/S rods and the resonant

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cavity. The proposed device offers high sensitivity and high quality factor compared with some recent works. Design scheme, sensing principle, and simulation results are discussed in the following Sections 2, 3, and 4. Finally, the main conclusion of our study is presented in Section 5.

2. BASIC PHOTONIC CRYSTAL DESIGN

The fundamental proposed structure is formed by silicon rods with refractive index of 3.42 and immersed in air matrix. The numbers of circular rods in X and Z directions are 21 and 21, respectively. So the total size of the device is 115.422 μm^2, which is compact and suitable for use in integrated circuits. The radius of each Si-rod r equals $0.245 * a$, where a is the distance between centers of two neighbouring rods known as lattice constant. By the plane wave expansion (PWE) method, the PhC indicates normalized frequency of PBG for transverse electric (TE) modes between 0.25581 $(\omega a/2\pi c)$ and 0.36315 $(\omega a/2\pi c)$ which is sufficiently wide for sensor design. So the frequency lies in the third window of optical communication. The band diagram of the basic PhC is illustrated in Fig. 1.

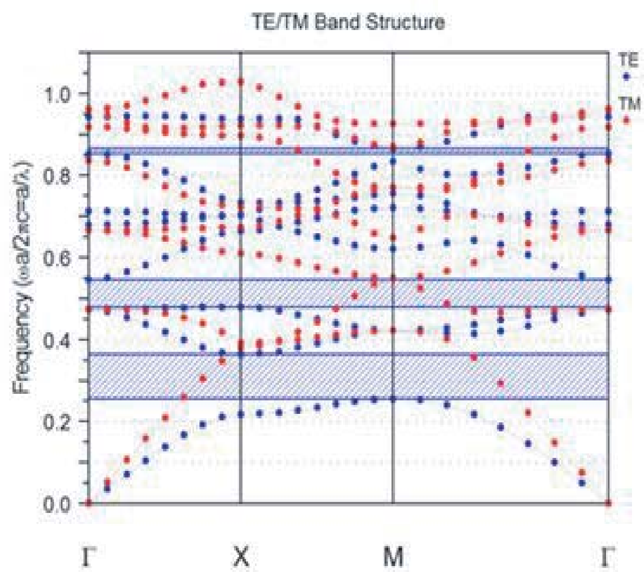

Figure 1. Band structure of dielectric rods in air background for TE polarization.

3. TEMPERATURE SENSOR DESIGN

In this section, our objective is to design an optical temperature sensor using two dimensional photonic crystals. For designing our proposed structure, we utilize a square lattice of silicon rods in an air matrix. The presented sensor consists of three main parts: (1) one input quasi-waveguide in the left part of the structure, (2) one output quasi-waveguide in the right part of the structure, and (3) one resonant cavity situated between the input and output quasi-waveguides. The schematic structure of the proposed device is depicted in Fig. 2(a).

As shown from this figure, the first part of the presented design is obtained by omitting several rods in X direction in the basic structure; its function is to guide the incident source toward the resonant cavity situated in the centre of the proposed device. The designed cavity is composed of an air hole covered by a silicon rod. The air hole is obtained by etching a silicon particle in the middle. So the newly formed defect is called core-shell (C/S) rods. The inner hole is called the core, and its surrounding layer is named the shell. The C/S particles are designed in the shape of axially symmetric rods. The radius of the internal and external rods of the C/S rod are $rc_1 = 0.062 * a$ and $rs_1 = 0.1 * a$, respectively. In order to improve the sensitivity, quality factor, and transmission efficiency, two steps have been used. The first step is to etch eight silicon particles located around the RC. As discussed previously, these

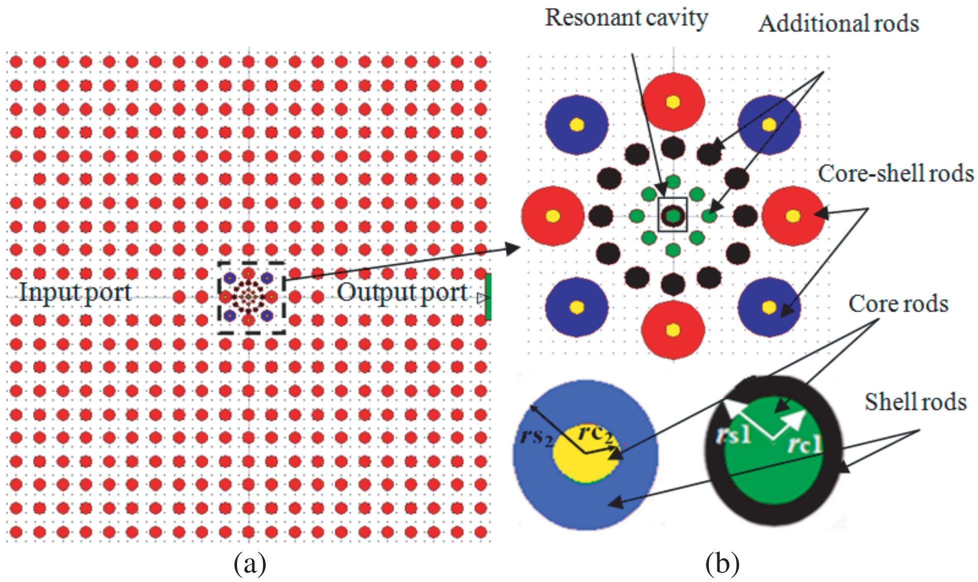

Figure 2. Schematic diagram of the (a) proposed temperature sensor, (b) resonant cavity and core/shell rods.

rods are etched in the middle of the silicon particles in order to get eight core/shell rods. Among these rods four of them have been moved horizontally and vertically with a distance d equal to 0.2 µm, shown in Fig. 2(b) in blue colors. As illustrated in this figure, the eight C/S rods form a circular ring shape around the cavity. Their inner and outer radii are $rc_2 = 0.062 * a$ and $rs_2 = 0.26 * a$, respectively. The second step is to add some additional rods around the RC. The radii of rods which are shown in Fig. 2(b) in green and black colors have the same radii as the core and shell of the resonant cavity, respectively.

4. SENSING PROPERTIES OF THE DESIGNED STRUCTURE

In this part, we study the sensing property of the presented device. The optical sensor is designed to detect the temperature over a range from 0 to 80°C. A Gaussian light beam emitted from a light source is applied at the input waveguide, will interact with the RC, and get detected with the monitor placed at the output waveguide. The sensing principle is based on the change of the refractive index (RI) of the Si rods when the temperature varies. The change of the RI rods with temperature is given by [13–15]:

$$n(T) = n0 + \alpha \Delta T \tag{1}$$

where n_0 is the refractive index of the Si rods at temperature 0°C, and α is the thermo-optic coefficient of the rods and given by 2.4×10^{-4}/°C. FDTD method is used to investigate the performance of the suggested photonic crystal temperature sensor. A fundamental parameter in evaluating the performance of temperature (T) sensor is the sensitivity (S_T) which can be expressed as [13]:

$$S_T = \Delta\lambda/\Delta T \tag{2}$$

where $\Delta\lambda$ is the change in the resonant wavelength, and ΔT is the change in the temperature. S_T is calculated in terms of pm/°C, and it should be as high as possible.

Figure 3 shows the normalized transmission spectra as a function of the wavelength with temperatures ranges from 0° to 80°C. As can be seen, the resonant wavelength mode shifts to higher quantities (red-shift) with the increase of the temperature. The resonant wavelength, sensitivity, and quality factor for different temperatures varying from 0°C to 80°C with increment step of 10°C are listed in Table 1. Every 10°C variation of the temperature results in a shift approximately 1 nm in the resonant peak.

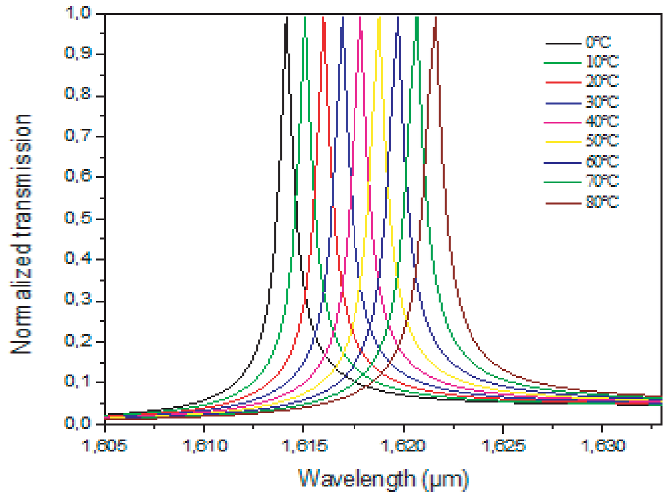

Figure 3. Transmission spectra of the proposed photonic crystal temperature sensor for different temperatures range from 0°C to 80°C.

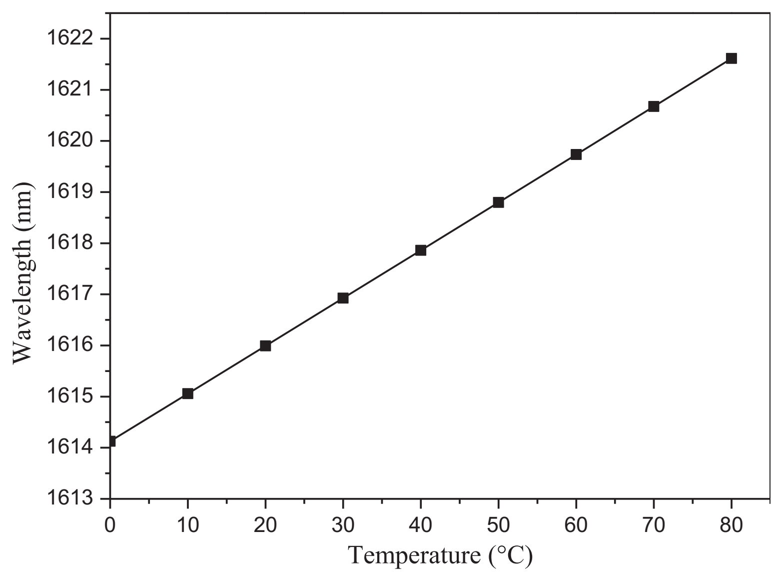

Figure 4. Linear relationship between the temperature and the resonance wavelength.

Using FDTD method, the characteristics of the PCTS are calculated. Fig. 4 indicates the resonant wavelength peak with respect to the temperature. It is obvious from the figure that the graph obtained is a straight line, and it can be said that the defect peak varies linearly with respect to the temperature change. Similarly, we have plotted a graph of the resonant wavelength peak as a function of temperature for three values of the outer radius rs_1. From Fig. 5, it can be noted that the three graphs obtained are linear. We conclude that when the thickness of the shell layer increases, the peak wavelength shifts towards higher quantities.

As illustrated in Table 1, the sensitivity and quality factor are respectively 93.61 (pm/°C) and 2506.5. The calculated functional parameters of the suggested PCTS are better than some previously structures proposed in recent articles [13–15, 18]. The comparison of the existing sensing structures is displayed in Table 2. The presented device offers high sensibility, high quality factor, and good linearly. In addition, the designed structure is very small with total size 115.422 μm^2. So we can use this kind of structure for photonic integrated components in optic and temperature sensor application.

Table 1. Resonant wavelength, sensibility and quality factor at different temperature levels.

T (°C)	λ (nm)	$\Delta\lambda$ (nm)	S (pm/°C)	Q
0	1614.125	/	/	2506.5
10	1615.057	0.932	93.2	2447.2
20	1615.991	1.866	93.3	2385.8
30	1616.925	2.8	93.33	2327.2
40	1617.861	3.736	93.4	2276.4
50	1618.797	4.672	93.44	2200.6
60	1619.735	5.61	93.5	2132.5
70	1620.674	6.549	93.56	2070
80	1621.614	7.489	93.61	1979.9

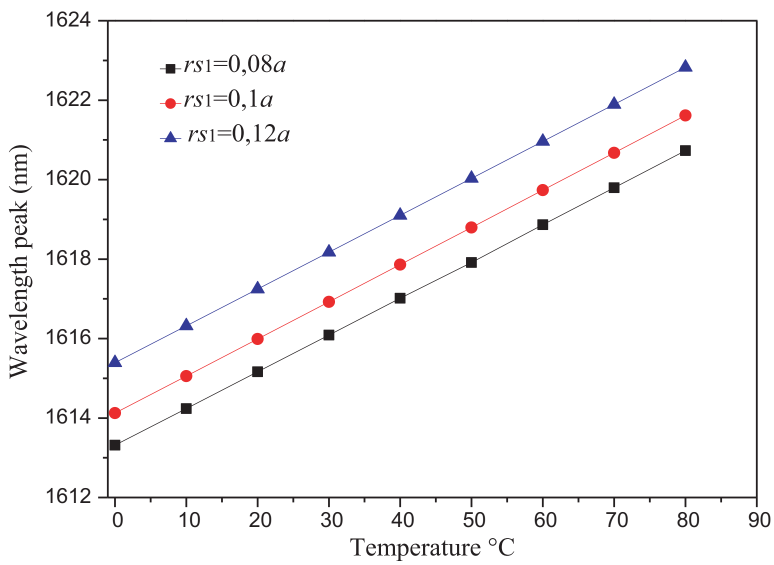

Figure 5. Linear relationship between the temperature and the resonance wavelength for three values of rs_1.

Table 2. Comparing our results with some previous works.

Reference	Year	Quality factor	Sensitivity (pm/°C)
[15]	2011	/	6.6
[14]	2016	/	84
[13]	2018	749.58	59.25
[18]	2019	415.7	88.7
This work	2019	2506.5	93.61

5. CONCLUSION

In this study, we investigate an ultra-compact optical sensor based on a coupling resonant cavity and two inline quasi-waveguides for detecting temperature variation. The mechanism of the detection is based on the principle that if a temperature is applied to a sample the refractive index changes leading to variation in its resonant wavelength. By every 10°C variation of the temperature, results in shift approximately 1 nm in the resonant peak. Our presented design reveals high quality factor and high sensibility compared with some recent works. The proposed sensor is very small with total size 115.422 μm^2, which is suitable for nanotechnology based sensing applications.

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