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Design of an Ultra-Compact and Highly-Sensitive Temperature Sensor Using Photonic Crystal Based Single Micro-Ring Resonator and Cascaded Micro-Ring Resonator

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Abstract

In the present report, a photonic crystal based micro-ring resonator (MRR) structure is proposed which is very compact in size and has very fast response and is employed for temperature sensing purpose. Temperature sensing application for both the single MRR and cascaded MRR is illustrated in this paper. The sensitivity of the reported structure is increased from 2.9 nm/°C to 3.4 nm/°C by cascading two MRR. The refractive index of the material is subjected to change with the variation in temperature which results in the shift of the resonant wavelength of the proposed sensor. The finite difference time domain (FDTD) simulation is utilized to see the transmission spectrum of the proposed structure and analyzing the shift in the resonance wavelength the temperature is calculated. The proposed design is simple, reliable and may be integrated into different transducer and sensing applications.

Keywords Temperature sensor · Photonic crystal · Photonic band gap · FDTD simulation · Micro-ring resonator

1 Introduction

Nowadays, photonic crystal (PhC) has been attracting great attention due to its potential in realization of various nano and opto devices. It has the eminent property to confine and manipulate the light propagating through the crystal [1]. The vast range of architectural parameters of a photonic crystal facilitates to supervise the optical properties of photonic crystals based devices. The concepts of photonic crystals were explained by two researchers named E. Yablonovitch and S. John in the year of 1987 [2, 3]. Researchers find its many

applications in optical filters [4], optical switches [5], logic gates [6], sensors [7, 8], etc.

For the advantages like flexibleness in miniaturization and also for the bandgap properties, nowadays PhC based devices are playing an important role in the sensing purposes. The band gap of a PhC prohibits a band of wavelengths to propagate through the crystal and for this reason defects are introduced in the PhC so that the prohibited wavelengths can be propagated through the defects and this is the basic requirement to design a PhC based optical device. Recently, new fields of research based on optical sensing like force sensing,

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refractive-index sensing, temperature sensing, salinity sensing etc. [7–11] are being explored. Basically, with the variation of the sensing parameter the variation in the refractive index (RI) and physical properties of material take place and this property of PhC makes it capable for sensing applications. It has some obvious advantages over electronic sensors which include very high sensitivity, transmission of huge data with high speed [8].

As the PhC micro-ring resonator (MRR) is very much sensitive to the lattice constant and radius of rods, therefore it gives more selectivity and sensitivity comparing with other waveguide based sensors. PhC based MRR is also very compact compared to other photonic devices. In the past years, different structures are proposed by different researchers to design temperature sensors [5, 10, 12–16]. Recently, M. Rahouene et al. proposed a two waveguide coupled superellipse structure of MRR to be used as a thermo-optic switch which posses the sensitivity of 2 nm/°C having the footprints of 277 μm^2 [5]. In [10], a PhC sensor is demonstrated for temperature sensing in which the wavelength shift took place when an external effect is applied to the whole structure. The sensor has the sensitivity of 2 RIU/°C and footprint is around 624 μm^2. Another temperature sensor was realized by R. Zegadi et al. using two-dimensional PhC based MRR having the sensitivity of 92.3 pm/°C and having the size about 108 μm^2 (approximate) [12].

The sensitivity of the reported structure is increased from 2.9 nm/°C to 3.4 nm/°C by cascading two MRR and also has very small footprint of around 45 μm^2 for single MRR and around 125 μm^2 for cascaded MRRs.

Basically, two approaches are practiced for the photonic crystals based sensing mechanism. One approach is based on intensity variation as described in ref. 17 and the other one is spectrum analysis which utilizes the shift in resonance wavelength that is used in the present manuscript. It is most widely used for the sensing of different physical parameters using photonic crystals. The proposed work is based on the spectrum analysis which considers the variation of resonance wavelength.

The temperature sensor has a broad range of applicability in the field of defence, civil, chemical, semiconductor industry, metal production and for many more domains. The

temperature monitoring is also important to estimate the structural health of the device. The proposed design is simpler and more compact. Moreover, it provides a high quality factor, very fast response and also the high sensitivity.

The reported article is summarized in the following manner: in section 2, we briefly introduce the PhC based MRR; section 3 describes the operation concept of the temperature sensor; in the section 4, design of temperature sensor using single PhC based MRR is presented; in section 5, design of cascaded PhC based double MRR is portrayed; in section 6, some functional parameters of the proposed device are discussed and finally, in section 7, the results are concluded.

2 Theory

In the PhC the periodic organization of two dielectric materials gives the flexibleness in the manipulating and controlling the propagation of light. PhCs are arranged in two different configurations: a) rods in the air type structure and b) holes in the slab, as shown in Fig. 1. Due to the periodic arrangement in the PhC a photonic band gap(PBG) is created which doesn't allow a wavelength band to pass through the regular photonic crystal structures. The rod based photonic crystal structure has a wider band gap comparing with the hole type structures and also the geometries of the hole type structures are more complex than rod-like structure [5]. Hence, we chose 2D–rod type structure with the array of Si-rods in square lattice.

In the present report, the MRR structure is designed using point defects and line defect to form a ring and the propagation waveguide respectively. A source of continuous wave (CW) "mode" type is given through input port to be detected at the output port, as depicted in Fig. 2. The device structure is quite simple using 2D PhC square lattice structure with line defect and MRR. All rods in the whole structure are of uniform radius, which is quite easy to fabricate. The ultra-compact size with high sensitivity is advantage of the present device structure over previously reported work.

Fig. 1 Different configurations of PhC arrangement: **(a).** rods in the air (square lattice) **(b).** slab with the air holes (triangular lattice)


a   b
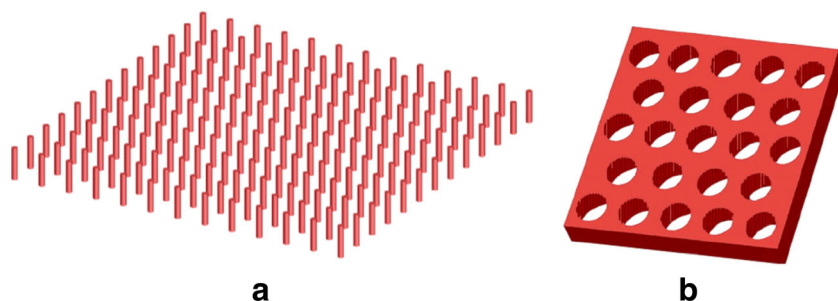
3 Operation Concept of Temperature Sensing

The main idea of the design is based on the use of PhC based MRR [18], where the optical intensity is enhanced by the input pulse. When the light of the operating wavelength is propagated through the ring due to multiple round-trips the light builds up in intensity as the constructive interference occurs which is represented by the following equation [19]:
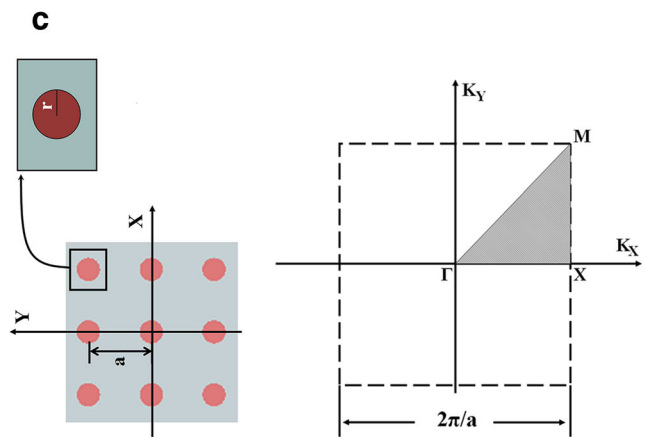
$$m\lambda = 2\pi R. n_{eff} \quad (1).$$
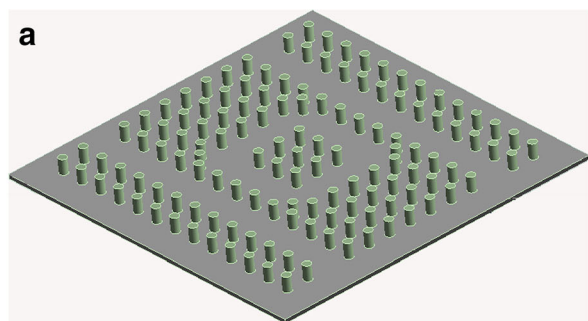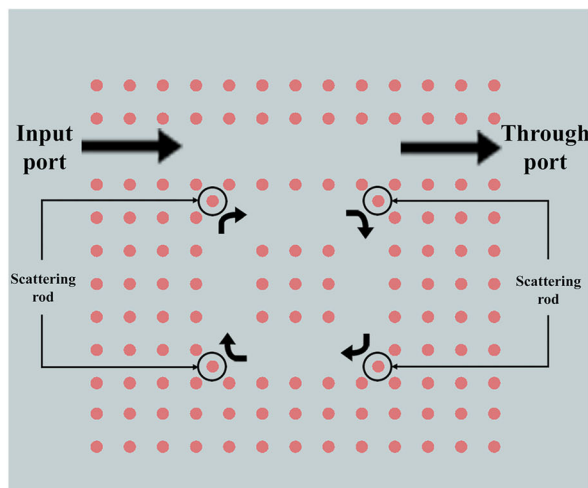
where, m denotes an integer (m = 1,2,3,.....), λ stands for the input wavelength, n_{eff} represents effective refractive index, R denotes the ring radius. The resonance condition of MRR can be varied by changing temperature of the device. This temperature variation results in the change of RI and structure of the material of the device and consequently, there is a wavelength shift towards the higher wavelength range (i.e. red shift) in the device. Thus, the resonant wavelength is tuned with temperature.

Due to the variation of temperature, the permittivity as well as the dimensions of the semiconductor dielectric material changes which ultimately change the central frequency of the PBG of the PhC. In the proposed scheme, Si rods are arranged periodically in the background of air. With the increase in the ambient temperature, the value of the lattice constant remain unchanged as with the expansion of the Si rods, the shrinkage in the air medium also takes place. The changed radius of Si rods can be obtained from the following expression [20].

$$r = r_0 + \alpha r_0 \Delta T \quad (2)$$

Where, r_0 stands for the radius of Si rod at room temperature, α denotes the thermal expansion coefficient of the medium and ΔT denotes the change in the ambient temperature.

The RI of a solid dielectric does not change directly for change in temperature but changes due to the change in density of the material for temperature variation. The mathematical expression of RI variation due to temperature effect (increase) is written as below [21]:

$$n_{eff} = n_0 + \alpha \Delta T \quad (3)$$

where n_0 = RI at 0 °C, α is the thermal expansion coefficient which is related to the variation of the radius of the Si rods and for Si, α is 1.8×10^{-4} /K [22, 23] and ΔT denotes temperature variation (increase). With the increase in the temperature, the RI increases and so the resonant wavelength get shifted.

Table 1 Design specifications of proposed structure

Sl. No.	Parameters	Specification
1.	Design structure	Rods in air
2.	Lattice design	Square lattice structure
3.	RI of Air	1
4.	RI of Si	3.45
5.	Source wavelength band	1.3 μm - 1.6 μm
6.	Resonant wavelength	nearly 1463.92 nm (at 25 °C)
7.	Rod rdius (r)	120 nm
8.	Lattice constant (a)	540 nm
9.	Number of rods along the X and Y directions	13 × 13
10.	Footprint	45 μm²
11.	Substrate material	Si

Fig. 2 Proposed structure of PhC based single MRR: **(a).** Perspective view, **(b).** Front view
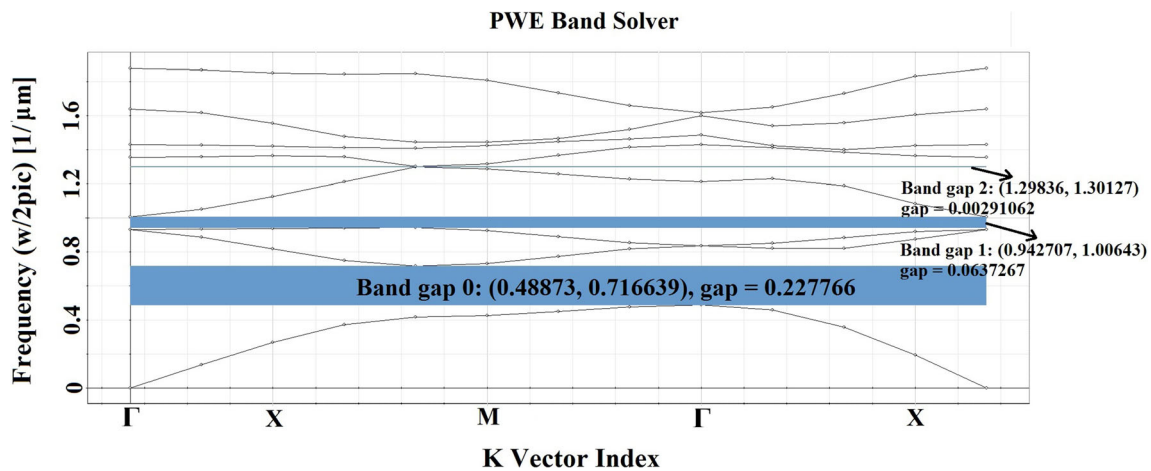
PWE Band Solver

Fig. 3 Band gap structure of the reported PhC structure for TM mode

4 Temperature Sensor Using Single PhC Based MRR

4.1 Proposed Design for Single PhC Based MRR

In the literature [8–11], various designs of sensors based on PhC are demonstrated. Such devices depend on many parameters with high precision of selection of rod's radius, the lattice constant and the permittivity of the dielectric materials. The proposed design is also dependent on these parameters. The perspective view of the proposed design obtained from finite difference time domain (FDTD) simulation is illustrated in Fig. 2. The two dimensional FDTD simulation environment is utilized for the simulation of the structure using a simulation platform developed by Lumerical [23–25]. The height of each Si rod is taken as 360 nm. The ratio of the radius of the rod to the lattice constant (r/a) is taken as 0.22 which is selected through the comparison and simulation and is suitable for wide band gap of Si rod type structure so that light can propagate properly through the proposed design. Therefore, the lattice constant of the structure and the radius of the rods are optimized as 540 nm and 120 nm respectively. The number of rods arranged along the X and Y directions are 13 and 13, respectively. The scattering rod is introduced in the structure to improve spectral selectivity as well as the coupling efficiency at four corners of the cavity, as implemented by S. Robinson et al. [4]. The coupling length is optimized based on the literature survey and through FDTD based numerical simulation. The optimized value of four lattice distance is 2160 nm. All other optimized parameters using FDTD simulation are indicated in Table 1.

The OptiFDTD software is used to find the band-gap structure of the reported design before the introduction of defects in which plane wave expansion (PWE) method is utilized (Fig. 3). The normalized frequencies obtained for the PBG ranges from 0.48873 to 0.716639, from 0.942707 to
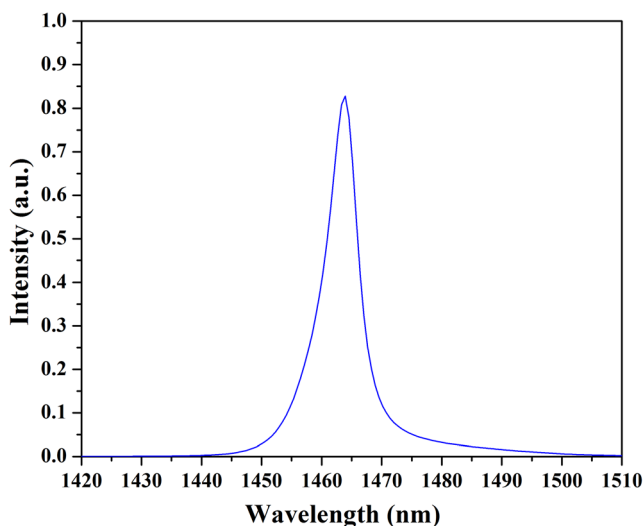

Fig. 4 Output normalized intensity of proposed single MRR design at 25 °C
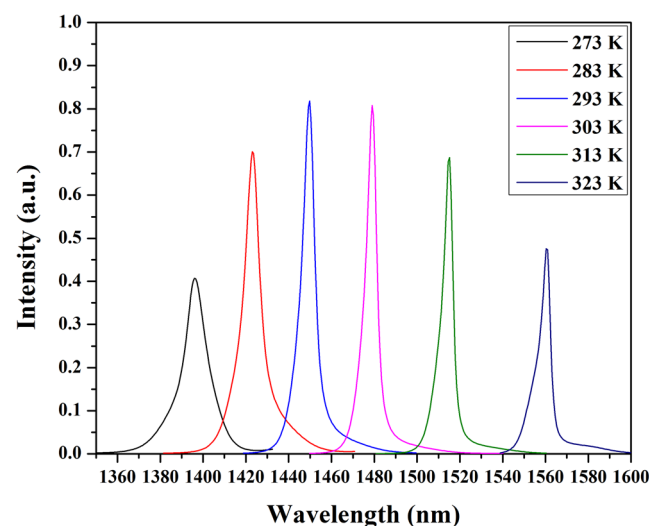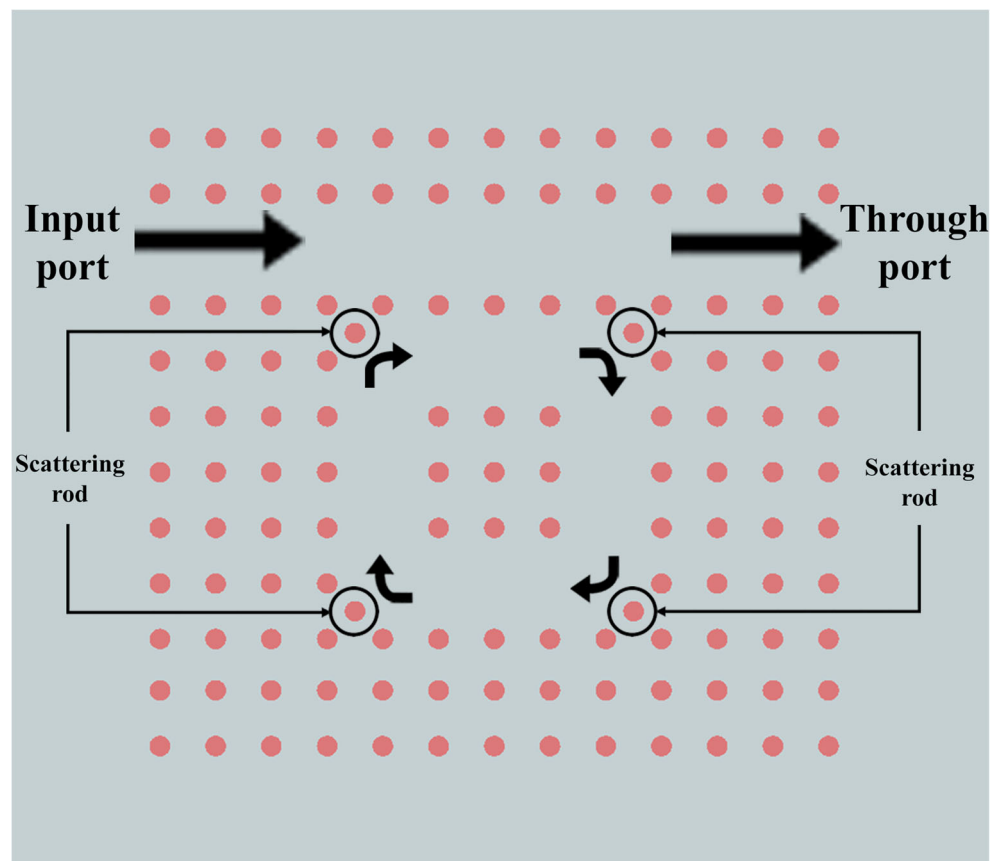

Fig. 5 Output normalized intensity at different temperatures of single MRR structure at the drop port

Table 2 Variation of resonance wavelength according to temperature

Temperature (°C)	Resonance wavelength (nm)	Wavelength shift
0	1395.99	
10	1422.98	27 nm
20	1449.81	27 nm
30	1478.94	29 nm
40	1515.21	36 nm
50	1554.91	39 nm

1.00643 and from 1.29836 to 1.30127 for TM mode (Fig. 3) which corresponds to the three wavelength intervals from 1395.4 nm to 2046.1 nm, from 993.6 nm to 1060.7 and from 768.4 nm – 770.2 nm, respectively. The first range of wavelength falls within the third optical communication window which is used as the wavelength range for sensing of the proposed structure. Therefore, to ensure and effective sensing the source wavelength range is chosen from 1395 nm to 1600 nm. The perfectly matched layer (PML) is employed as a boundary surface to minimize back reflections. In the report, the substrate material is Si [26]. In the proposed structure the high RI material Si rods are surrounded by the lower RI material air only.

4.2 Simulation Results

This section describes the optical sensing results and performances obtained for the proposed structure. The transmission graph at the output of proposed sensor at room temperature 298 K (25 °C) at the drop port is shown in Fig. 4.

The output transmission of the proposed device for temperature range 0 °C - 50 °C with step of 10 °C using FDTD simulation is shown in Fig. 5. The values of the resonant wavelengths at different temperatures are given in Table 2.

It clearly indicates that, a red-shift takes place with the increase in the temperature. Thus tuning of resonant wavelength by temperature effect can be employed for the modeling of temperature sensor.

5 Temperature Sensor Using Cascaded Double MRR

5.1 Proposed Design for the Cascaded PhC Based MRR

In the proposed design two MRRs are serially cascaded where the output light from the drop port of MRR1 acts as the input for MRR2 and the final output light is obtained from the drop
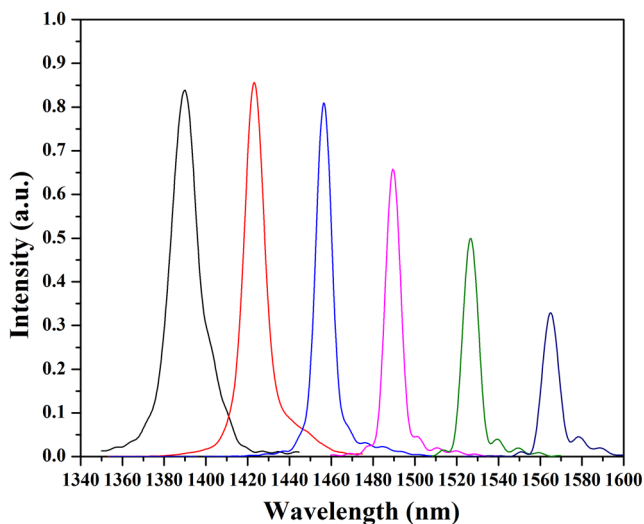

Fig. 6 Proposed structure of serially cascaded PhC based double MRR

Fig. 7 Output normalized intensity at different temperatures for cascaded MRR structure

Fig. 8 Sensitivity graph of single MRR structure

port of MRR2. In this structure, 18 rods and 21 rods are placed in the square type lattice structure respectively along the X and Y directions. The other design parameters are same as given in Table 1. The front view of the proposed structure is depicted in Fig. 6.

5.2 Simulation Results

The output transmission curve for the cascaded MRRs for the temperature ranging from 0 °C to 50 °C are portrayed in the Fig.7 and in the Table 3 the resonance wavelengths for various temperatures are illustrated.

6 Discussions

In this paper, the temperature variation is studied from 0 to 50 °C, which can be achieved by environmental changes easily. So, this device can be used as temperature sensing application for low temperature range of environmental changes as well as low temperature furnace or heat source. As the desired

Table 3 Variation of resonance wavelength according to temperature min the cascaded MRR

Temperature (°C)	Resonance wavelength (nm)	Wavelength shift
0	1390.04	
10	1423.04	33 nm
20	1456.55	34 nm
30	1489.41	33 nm
40	1526.6	37 nm
50	1564.9	38.3 nm

temperature studied for the present case (0-50 °C) is quite low and the dimension of the whole structure is very small (about 45 μm^2 for single MRR and 125 μm^2 for cascaded MRRs), and also the thermal conductivity of silicon is about 130 W/m-K, which is very high in compared to air (0.024 W/m-K), so the temperature distribution along the whole structure is taken as uniform and the dependence of RI on the temperature is taken linearly as

$$n_{eff} = n_0 + \alpha \Delta T$$

Due to change in RI of the material of rods, the resonance mode of the ring is changed. This change in resonance wavelength depends directly on the temperature. In this way, the structure is used to sense the temperature.

The FWHM depends on the lattice constant of the crystal structure and the radius of the rods which are optimized
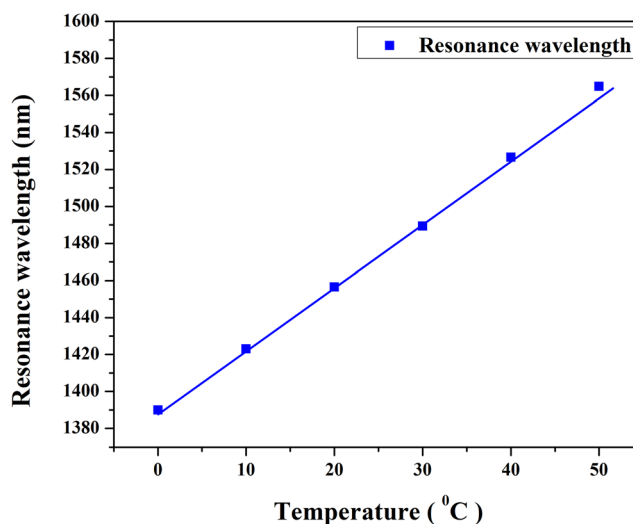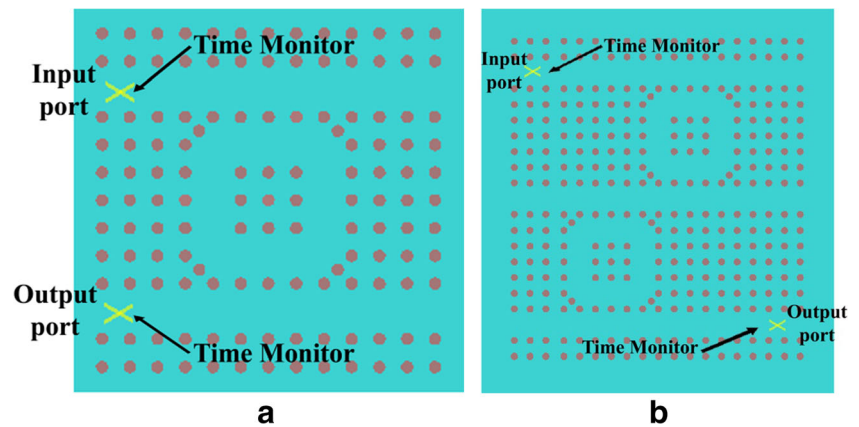

Fig. 9 Sensitivity graph of cascaded MRR structure

Fig. 10 Schematic diagram of (a). Single MRR structure (b). Cascaded MRR structure to calculate the response time

through numerical simulation to achieve higher sensitivity. The FWHM of the device can be minimized by changing the lattice constant and the rods radius which will reduce the sensitivity of the proposed device. The optimized values of lattice constant and the rods radius are considered in the manuscript.

The proposed temperature sensor is designated by the succeeding design parameters:

6.1 Sensitivity

Sensitivity (S) = $\partial\lambda/\partial T$, can be expressed as the shift in wavelength per unit change in the temperature, where $\partial\lambda$ is the change in wavelength and ∂T denotes the change in temperature.

For the first proposed structure, the sensitivity is equal to 2.9 nm /°C. Figure 8 is the sensitivity curve of our proposed device, which clearly indicates that the response is almost linear up to 50 °C and furthermore, it may also be concluded that the temperature of 50 °C will act as a threshold temperature. And therefore, the almost linear response of the device's wavelength shift is utilized for temperature sensing purpose and also can be utilized for the detection of the threshold temperatures, like in case of [10].

In the double MRR structure, the sensitivity is equal to 3.4 nm /°C. The sensitivity curve of the proposed device is depicted in Fig. 9 and the response is linear up to 50 °C. It can be also concluded that, cascading of two MRR also increases the sensitivity.

6.2 Response Time

The response time is calculated using FDTD based numerical simulation method [23]. In order to calculate the response time of the proposed device (Fig. 10) the time monitors are placed at the input port and the output port respectively. The response time of the proposed single MRR based temperature sensor is around 80 fs and the response time of the proposed cascaded structure is around 124 fs respectively.

7 Conclusion

In this paper, two-dimensional square lattice PhC based single MRR structure and cascaded double PhC based MRR structure is designed for temperature sensing applications. Simulation results show that the proposed single MRR structure has high sensitivity of about 2.9 nm/°C with very small footprint ($\approx 45 \ \mu m^2$) and fast response time (≈ 80 fs). By cascading two MRR the sensitivity of the proposed device is increased upto 3.4 nm/°C and having the footprint of 125 μm^2. Dynamic range of the proposed structures is from 0 °C to 50 °C. Furthermore, the design is simple, reliable, stable and can be integrated into various transducer and sensing applications.

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