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Tapered side coupled photonic crystal ring resonator as a refractive index sensor

Anas Ashraf[1], Partha Saha[2]
[1]*Student, Harcourt Butler Technical University, Kanpur, U.P.*
[2]*Assistant Professor, Harcourt Butler Technical University, Kanpur, U.P.*
Corresponding Author: Anas Ashraf

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ABSTRACT: In this project, a refractive index gas sensor based on two-dimensional (2D) photonic crystalmicrocavity (PCM)has been proposed. Ithasa microcavity along a W1 waveguide which consists of a ring resonator; with three side coupled holes. The side coupled holes are tapered to increase the quality factor; which also increased the sensitivity of the device.The quality factor and the sensitivity of the refractive index based sensor have been found to be 15,789and 500 nm/RIU respectively. The higher performance of the quality factor and sensitivity with the tuning of the design makes the sensor a good candidate for the application of gas sensing.

KEYWORDS: 2D photonic crystal, photonic crystal microcavity, refractive index gas sensor, optical sensor, quality factor, sensitivity.

I. INTRODUCTION

Design of sensors can be done using different techniques but all have their advantages and disadvantages. Such as semiconductor sensors, ionization sensors and electrochemical sensors has the advantage of low cost and simple in execution [1]. However, the temperature and high-power utilization influence the performance of these sensors in terms of decreasing sensitivity. In addition, because of measuring probes, an undesired electromagnetic impact happens. On the other hand, optical sensors based on optical signal transformation, have low power consumption and fast response.

In the field of optical sensors, photonic crystals (PhCs) are having promising properties for the design of sensors. The properties of PhC include compactness, low loss, flexibility in designing and on-chip-integration[2]. The PhC has interesting feature of having photonic band-gap in the structure. The photonic band-gap is a phenomenon in which light of certain wavelength is reflected back when launched into the structure.The PhC is very flexible since by simple tuning of the structure the nature of photonic band gaps can be changed. Therefore, this flexibility of the PhC has made it possible to innovative in them and has opened numerous additional opportunities for ultra-reduced size and huge estimation range of refractive index [3]. Several optical sensors work on computing the alteration in the index of refractionfor instance, surface plasmon resonance, interferometry in porous silicon and calorimetric resonances but these strategies need enormous area beams and generally huge detecting region [4].In optical resonance advancements, photonic crystal (PhC) based sensors have pulled in significant attention due to their large spectral sensitivity and miniaturized size[5]. The photonic crystals have been used in different applications as multiplexers, sensors, Filters etc. These are also having scope in the area of defence, security, environment and aerospace[6,7]. Intense field confinement and high-quality factor in photonic crystal-based resonator have been achieved [8].PhCs may be utilized to constrain light in abridged index of refraction region that allow intense light matter contact and provide high sensitivity [9].

Thebasic idea of theproposed design is derived from a miniaturized photonic crystal microcavity; having a ring resonator along the W1 waveguide; with three holes on both side of the resonator and one air hole at the centre of resonator[10]. In the paper [10], a methane sensoris designed utilizing the gas sensitive material cryptophane E. The quality factor (Q) and the sensitivity of that design is 12,923 and 363.8 nm/RIU respectively. However, in the proposed structure tapering of the three side holes has resulted in an improvement ofhigh-quality factor and sensitivity of 15,789 and 500 nm/RIU respectively.

II. THEORETICAL ANALYSIS OF PCMs

The well-known Finite-difference-time-domain (FDTD) algorithm is utilized to compute the electromagnetic field progression and the

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transmission spectrum. The FDTD method solves the Maxwell equations to get the transmission spectra.

Here are the Maxwell's equations [11]

$$\frac{\partial Hx}{\partial t} = -\frac{1}{\mu}\frac{\partial Ez}{\partial y} \quad (1)$$

$$\frac{\partial Hy}{\partial t} = \frac{1}{\mu}\frac{\partial Ez}{\partial x} \quad (2)$$

$$\frac{\partial Ez}{\partial t} = \frac{1}{\epsilon}\left(\frac{\partial Hy}{\partial x} - \frac{\partial Hx}{\partial y} - \sigma Ez\right) \quad (3)$$

Here ε signifies the permittivity, μ signifies permeability, σ is the conductivity.

A photonic crystal cavity can be designed by altering the size of holes or by deleting holes in the periodic arrangement. The sensing mechanism depends on the shift in the resonantwavelength of the cavity with respect to alteration in the index of refraction (RI) present in the cavity. Few important parameters are need to be considered for RI sensing application such as quality factor, sensitivity, mode volume and figure of merit (FOM).

Quality factor depends on the energy stowed inside the cavity. Therefore, to increase quality factor, the energy loss should be minimized.

The quality factor is statedbelow:

$$Q = \frac{\lambda}{\Delta\lambda}$$

Here, λ is the resonant wavelength and $\Delta\lambda$ is FWHM (full width at half maximum).

In general, the sensitivity is stated as [12]

$$S = \frac{\Delta\lambda}{\Delta n}$$

Here,$\Delta\lambda$ is the alteration in wavelength and Δn is the alteration in the index of refraction.

III. DESIGN OF PROPOSED PHOTONIC CRYSTAL STRUCTURE

Figure 1 illustrates the photonic crystal structures used for computation purposes. A 2D hexagonal lattice structure with air holes is chosen with dimensions of 17 and 15. In this particular structure arrangement, a ring resonator with 3 holes at each side of it, is made along W1 waveguide in Γ-K direction as depicted in the figure below. The parameters which are made for this particular structure in order to obtain desired results is chosen. The lattice constant (a) of the given geometry is made to be 0.42 μm and the hole radius is chosen to be 0.39a nm. The radius of the defected holes Ro is fixed at 200 nm.The value of slab delta is made to be 2.4. The wavelength at which launching is to be taken place is 1.55 μm. Also, the stop time of the simulation is taken to be 15000 for each of the simulations that are performed for examining the performance for this structure.

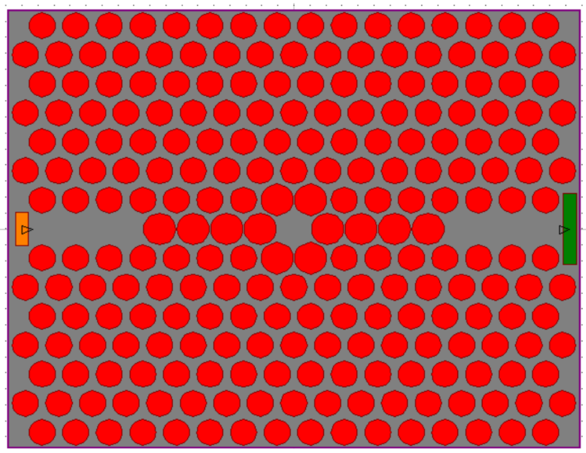

Fig. 1 Schematic diagram of proposed structure.

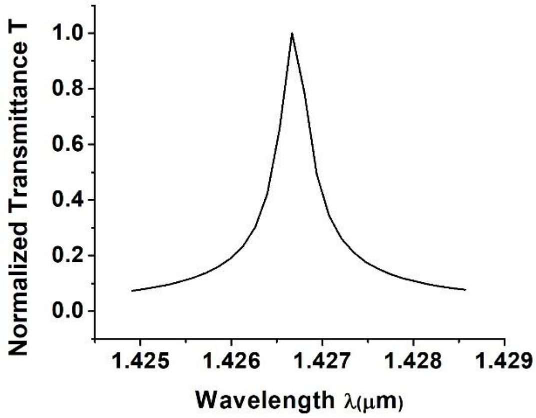

Fig. 2 Normalized transmittance graph when the cavity structure is uniform.

The resonant wavelength is at 1.4267 μm for the proposed structure. There is a shift of 0.1 nm when the refractive index is changed to 1.0004. This structure exhibits a sensitivity of 250 nm/RIU and a quality factor of 4,756. Since, the result obtained is not so good therefore, a slight modification in the side coupled hole radius is done. The modified structure has a side coupled holes with different hole radius as R3 = 163.8 nm, R2 = 180 nm and R1 = 190 nm as depicted in figure 3.

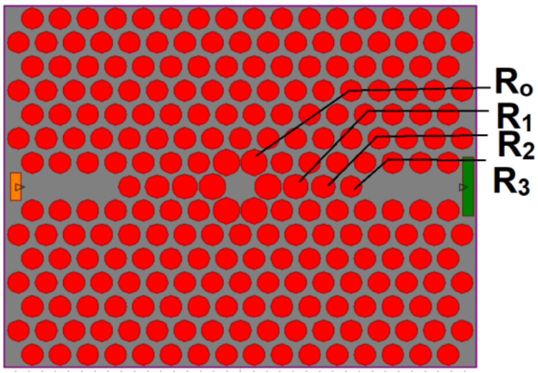

Fig.3. Modified geometry with different side coupled holes radius. R1 = 190 nm, R2 = 180 nm and R3 = 163.8 nm.

With these modifications, the quality factor enhances to 15,789 which is better than the previous structure. Later, when the refractive index is changed to 1.0004, the resonant wavelength gets shifted by 0.2 nm and exhibits a sensitivity of 500 nm/RIU which is also ample better as compared to previous geometry. Lastly, the refractive indices are changed to 1.0008, 1.0012, 1.0016 and 1.002 with the increment of 0.0004 ($\Delta n = 0.0004$) and the displacement in resonant wavelength after each increment in index of refraction (n) is shown in fig. 4. Whereas, the sensitivity obtained at each alteration is shown in the table1.

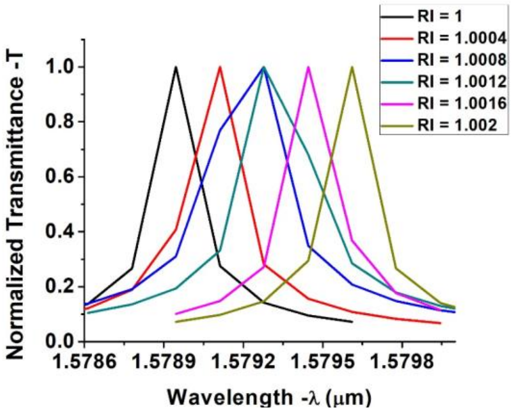

Fig. 3 Shift in resonant wavelength when RI is changed from 1 to 1.002.

Table 1. Sensitivity and shift in resonant peak at each alteration in refractive index

REFRACTIVE INDEX DIFFERENCE (Δn)	SHIFT IN RESONANT PEAK (nm)	SENSITIVITY (nm/RIU)
0.0004	0.2	500
0.0008	0.4	500
0.0012	0.4	333.3
0.0016	0.5	312.5
0.002	0.7	350

The highest sensitivity attained for the modified structure is 500 nm/RIU as depicted from the table 1. The resonant wavelength shift towards higher wavelength as the index of refraction increases from n = 1 to 1.002 with the increment of 0.0004 ($\Delta n = 0.0004$).

The sensitivity of the RI based gas sensor depends on the alteration in index of refraction (Δn). The modified structure shows a relatively high sensitivity of 500 nm/RIU when there is a difference of 0.0004 and 0.0008 in refractive index as shown in fig. 5. It can be seen that sensitivity firstly decreases and then it gained again a moderate value of 350nm/RIU when $\Delta n = 0.002$.

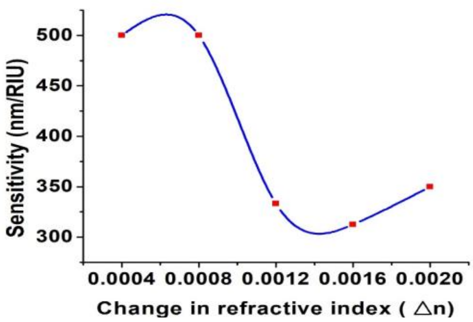

Fig. 5. Change in the sensitivity with the alteration in index of refraction.

Table 2 shows the comparison of the proposed tapered side coupled ring resonator with the similar structure reported earlier in terms of quality factor and sensitivity. It can be seen that the proposed structure has better values of both the parameters as compared to other reported structure.

These benefits of the proposed structure open the possibilities for sensing small change in refractive index.

Table 2. Comparison of proposed geometry with similar geometries in terms of quality factor and sensitivity.

DESCRIPTION	QUALITY FACTOR (Q)	SENSITIVITY (nm/RIU)	REFERENCES
High transmission PhC for biosensing application	2966	131.7	[13]
Ultracompact refractive index sensor	3,820	330	[14]
A miniaturized photonic crystal microcavity	12,923	363.8	[10]
Performance optimization of PhC resonator	10,000	400	[15]
Tapered side coupled ring resonator	15,789	500	Proposed structure

IV. CONCLUSION

In this project, a refractive index gas detector based on 2Dphotonic crystal has been proposed. The cavity is designed with a ring resonator having three side coupled holes along the W1 waveguide. The photonic crystal microcavity (PCM) confines the light and the output is taken from the other side of W1 waveguide. This microcavity consists of three side coupled holes which are tapered in increasing fashion moving out from the center of the cavity. The tapering of the side coupled holes has resulted in an increased performance of the cavity. The quality factor and sensitivity of the sensor has been found to be high 15,789 and 500 nm/RIU. These high performances of the sensorare highly desirable for a gas sensor.

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