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Proceedings

2020 International Conference on Emerging Trends in Communication, Control and Computing

FEBRUARY 21-22, 2020

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IEEE Catalog Number: CFP19R72-ART

ISBN: 978-1-7281-1420-0

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2020 International Conference on Emerging Trends in Communication, Control and Computing (ICONC3)
Mody University of Science and Technology, Lakshmangarh, Feb 21-22, 2020

Photonic Crystal Cavities based Biosensors: A Review

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***Abstract*— The review paper is providing the brief idea of photonic Crystal Cavities (PCCs) structures and their applications for biosensing devices. The paper presents the review of different PCC structures with modified properties of sensing. For several optical sensing applications, different PCC structure with properties are described in details. The conclusion of reported work and result demonstrated that miniaturization of optical biosensors is possible by the different PCC structure. This PCC structure has flexibility in structure for different sensing applications.**

Keywords*— *Photonic Crystal (PhC), Photonic Crystal Cavities, Biosensors, Quality Factor, Sensitivity

I. INTRODUCTION

Photonic crystal is the latest technology for guiding the light at optical wavelength [1,2]. The structures of photonic crystal were projected over a long time ago [1,3]. Photons has neither the electric charge not the mass in rest position and cannot be trapped easily through electric charge. To confine the electron in a specific part, total internal reflection (TIR) phenomena is essential. For performing TIR phenomenon, the refractive index of core is higher than clad refractive index. Photonic crystal (PC) is a periodically arrangement of material having the different dielectric constant [4-6]. A PC structure is the low-loss dielectric medium or an artificial dielectric structure whose refractive index is periodically tempered [5,6]. It is a periodic arrangement of a material having low and high refractive index for the proper confinement of optical signal. These artificial dielectric medium structures are proficient to confine the photons in a small space for a long time. Photonic band gaps (PBG) [5] is the important property for transmission of optical signal. This PBG can preventing to propagate the light in certain direction with some specific frequency band, i.e. lies in photonic band gap. These cavity structures have been developed for several application as wavelength filter [7,8], modulator [9,10], gas sensors [11], biosensors [11-18]. The importance of sensors in the recent scenario is well recognized for the development of technological infrastructure of awareness of protection and environmental issues, high-precision information dispensation and data acquisition [14].

In PC structure, the cavity is formed by introducing some defect. The defect may be a point defect or line defect. This defect is the responsible for the transmission of the optical signal in PBG. The photonic structure is used in biosensing application due to compact size and high sensitivity structure. Several researchers are doing their work to design the different photonic crystal cavities-based structure to enhance the sensitivity of the sensor [19-22]. In this paper, a brief overview on PC cavity based optical sensor is introduced. Along with this brief overview, this paper provides the new perspective of further advancement in this area. In section 2, the different PC cavity structure is discussed and analysed. In section 3, different Gas and Biosensors are presented. In section 4, we provide a brief conclusion and future scope this area.

II. SENSING PRINCIPAL OF PC CAVITIES

As the different defected in PC cavity structure, cavity structure is dividing into ring cavity, Hm cavity, Ln cavity, shoulder couple cavity as shown in fig.1[23-29]. In fig.1 the holes are the air hole (refractive index η=1) as a clad. The structure is designed with the conducting material having the refractive index higher than the air as a core for the confinement of photon in this gap. For designing the different cavities structure there is some modification done in the periodicity of these air-holes. These cavities structure can perceive the change in refractive index (RI). For the detection of RI, the detection limit (C) of these PhC structure can be calculated by minimal resolvable wavelength shift and the measurement sensitivity (S).

The sensitivity is given by [23,38]

$$S = \frac{\Delta\lambda}{\Delta n} \tag{1}$$

The minimal resolvable wavelength shift ($\Delta\lambda_{min}$) is given by [30]

$$\Delta\lambda_{min} = \frac{\lambda_0}{10Q} \tag{2}$$

where, Q is the Quality Factor and λ_0 is the resonant wavelength. The detection limit (C) of the PhC structure is:

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$$C = \frac{\lambda_{min}}{S} \tag{3}$$

From eq (2) and eq (3) the detection limit has

$$C = \frac{\lambda_0}{10QS} \tag{4}$$

The detection limit is inversely proportional to Quality Factor and Sensitivity. For the better detection the detection limit is minimum or the quality factor and sensitivity is maximum.

III. OPTICAL SENSORS BASED ON PHC STRUCTURE

The PhC structure is designed for the Silicon (Si) material having the Refractive index 3.42. The lattice constant for the design structure (a=0.4μm) and r=0.3a. The schematic structure of PhC is shown in fig.1. Fig.1 shows the Schematic structure of ring cavity in photonics structure.

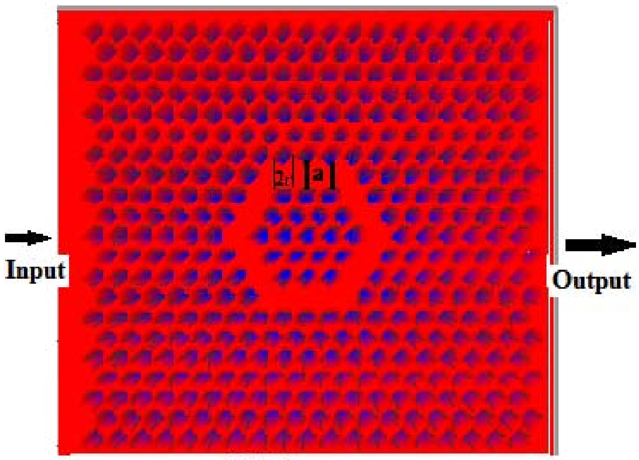

Fig. 1. Schematic structure of ring cavity in photonics structure

Fig 2(a) the ring cavity, where modification in periodic structure is done in a ring pattern. Fig 2(b) shows the communication of light because of ring defect. Fig 2(c) shows the spectrum of received light. In fig.2, applied signal is having a wavelength peak at 1550nm and received signal is having the wavelength of 1549nm, so a minor variation is occurred in resonant peak. Fig.3 to fig 6 shows the different cavity structure and their light confinement. From these figures we can say that the TE polarized in-plane direction and out-plane direction light can be strongly restricted in waveguide region because it will show the better TIR condition for optical signal and leakage of optical signal is less. In the ring structure the optical signal is divided into 2 parts, so confinement in out-plane direction is less. This ring structure is also work as a power divider for the specific ring diameter (spacing between two front surfaces).

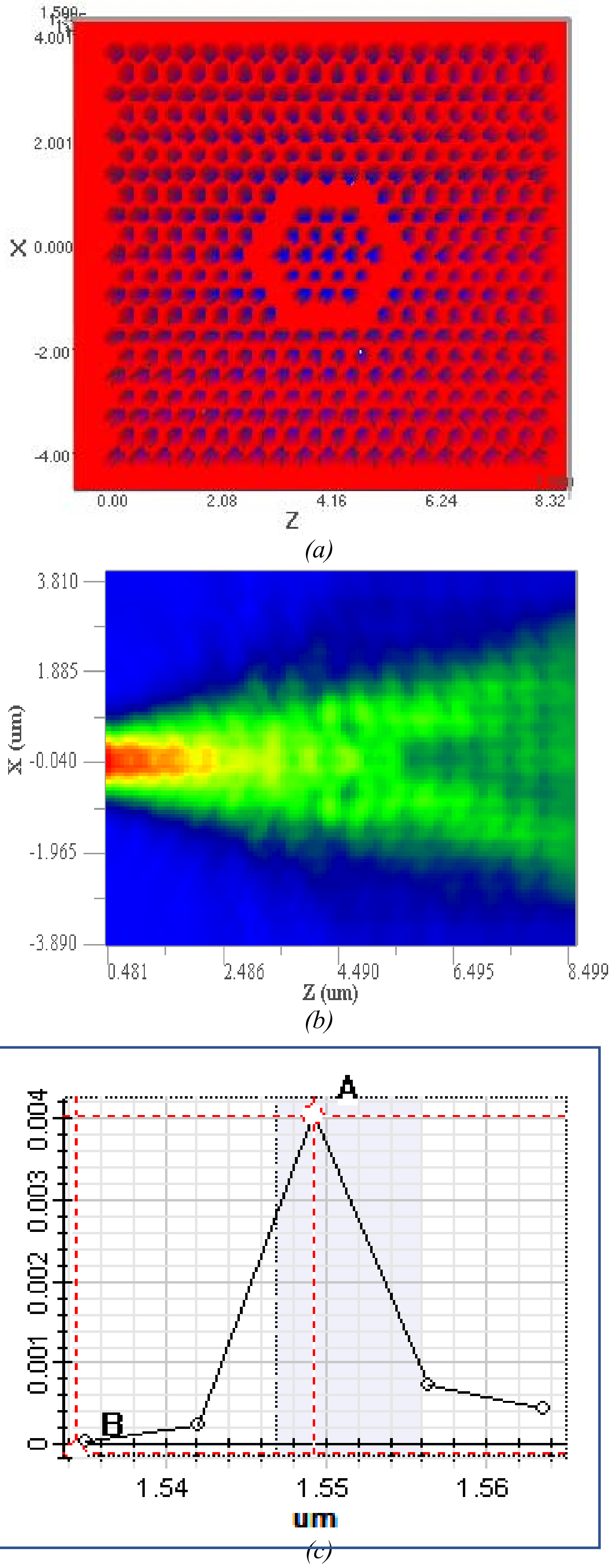

Fig. 2. Photonic cavity structure (a) ring cavity (b) Confinement of light and (c) Spectrum of received light for 1550nm wavelength

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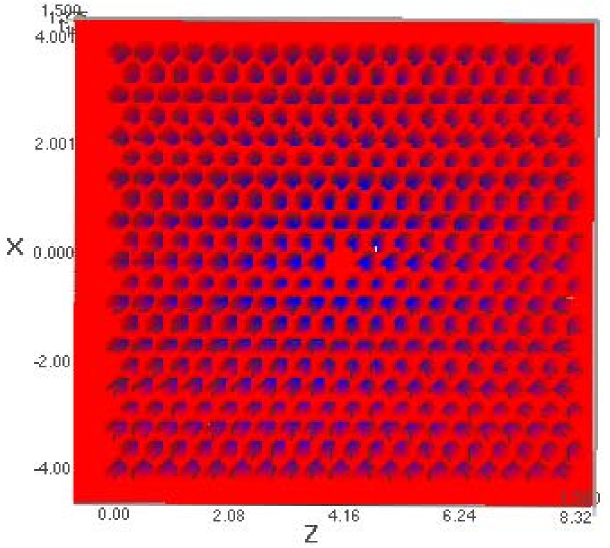
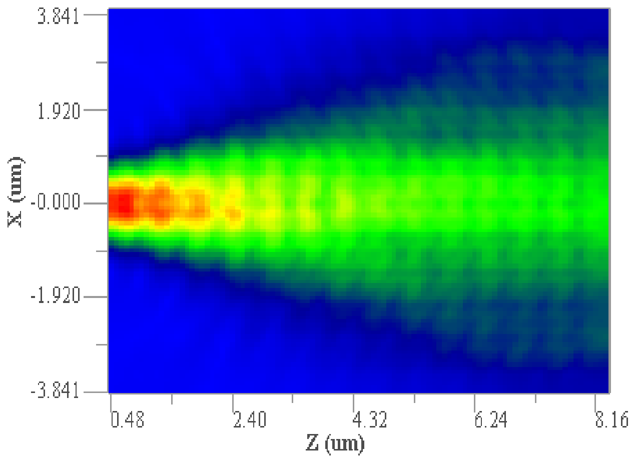
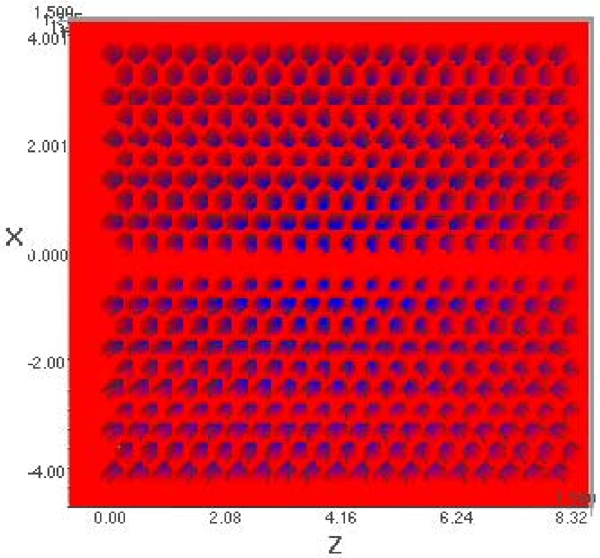


(a)

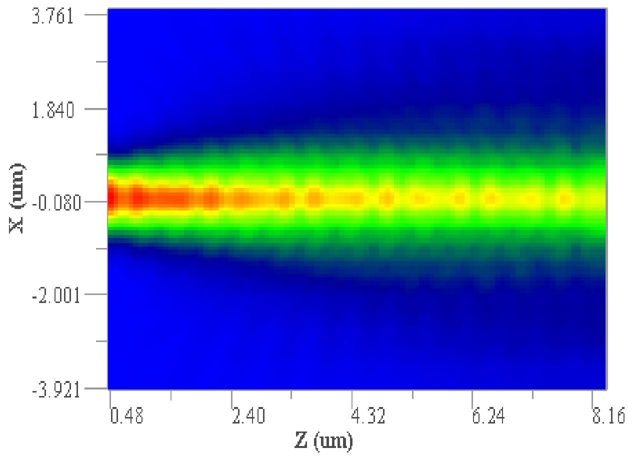


(b)

Fig. 3. Photonic cavity structure (a)single defect (L0 cavity) (b)Confinement of light

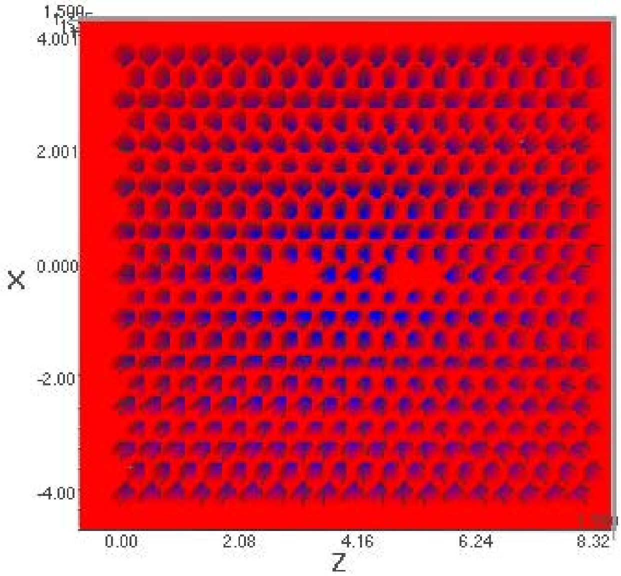


(a)

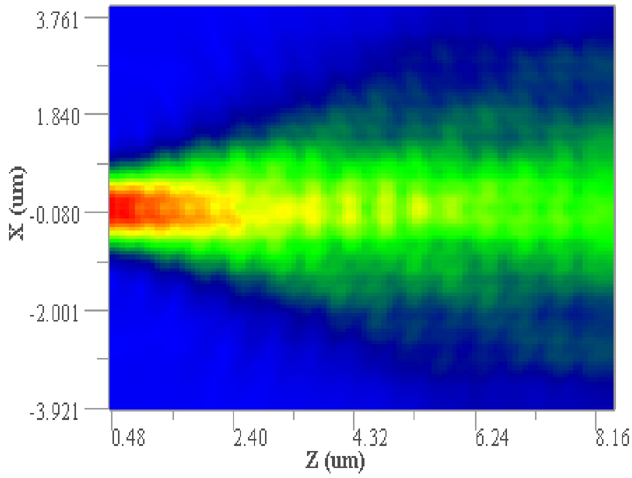


(b)

Fig. 4. Photonic cavity structure (a) waveguide cavity (b) Confinement of light at 1550 nm



(a)



(b)

Fig. 5. Photonic cavity structure (a) four-hole cavity (b) Confinement of light

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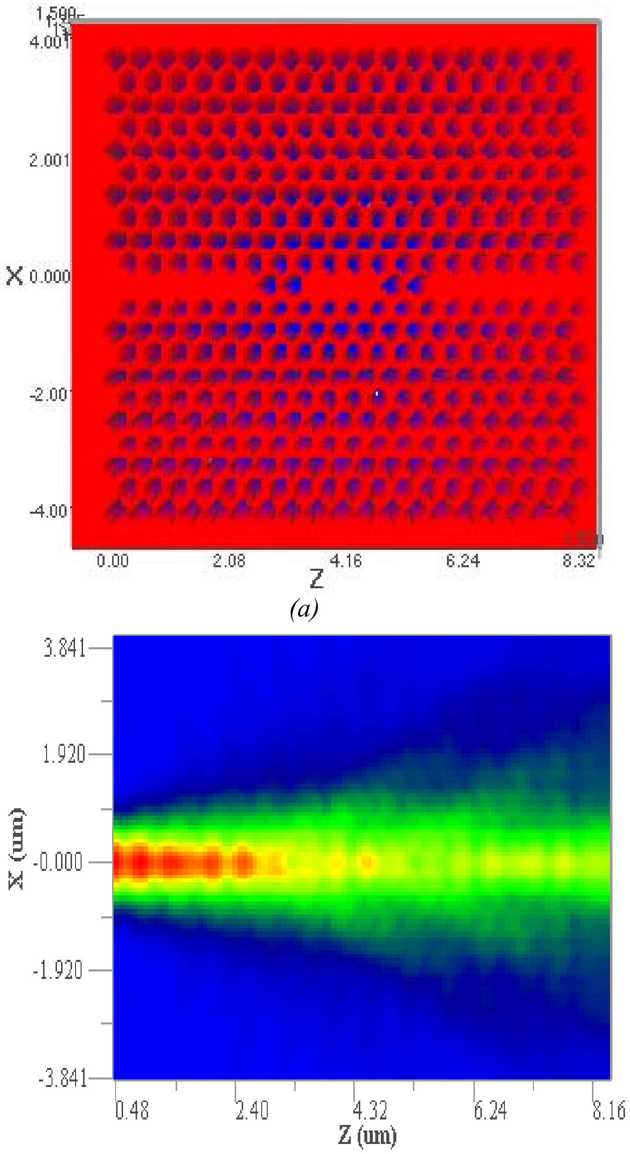

Fig. 6. Photonic cavity structure (a)Shoulder coupled cavity (b) Confinement of light

IV. Application of Photonic Crystal Structures

A. Refractive index-based sensor

As the above discussed structure, PhC cavities has strong light confinement. This confinement of light is because of TIR phenomenon. For a certain change in medium refractive index, penetrated in the air holes of PCC, the confinement of light may change as well as the resonant peak of the light is also changing. The change in resonant peak because of change in RI was first demonstrated in [30]. Table 1 shows the comparison sheet of different structure was given by many researchers [29-32].

The result shown in table 1, that higher sensitivity (S) and quality factor(Q) provide the better detection limit to sense the changes in refractive index. This detection for change in refractive index makes it suitable for several sensing application.

TABLE I. Comparative Study of Different Cavities Structure with Their Sensing Properties

Q	S (nm/RIU)	Detection Limit	Published year
400	155	0.018	2008
3000	63	0.006	2008
3820	330	0.001	2008
17890	500	0.0001	2013
107	330	1.24x10-5	2014
107	160	8.75x10-5	2015

B. Biochemical Sensor

The concentration of biochemical sample/ solution as a target analyte is directly related to the Refractive index. Several biochemical sensors are available to sense the concentration of glucose, protein analyte etc. These sensors exploit the change in RI by inducing the analyte in interaction part of optical signal for performing the sensing mechanism. Along with the advancement in structure of PhC for sensing of different RI medium, several biochemical PhC sensors were also projected and demonstrated. It was presented that changing the dimension of cavity would change the Quality factor of cavity and improve the shifting of resonant wavelength while size compactness is characteristic [33,34]. It was also reported that a PhC cavity possibly will able to sense protein molecules small as 2.5 fg, [35].

C. Gas Sensor

The airhole structure in PhC can also sense the change in concentration of gases in a mixture. Different gases have the different refractive index. The refractive index would change as shown in table 2 with the concentration variation and refractive index variation can change the resonant peak of the optical signal. The sensing of gas concentration for two different gases mixture with different refractive indices was proposed in [36-37]. The proposed design in [38] has the quality factor 380,000 for gas sensing.

TABLE II. Refractive Index of Gases for1570nm Wavelength [37]

S. No.	Gases	Refractive Index
1	Air	1:000265
2	Carbon dioxide	1.000407
3	Carbon monoxide	1.000302
4	Methane	1.000407
5	Nitrous oxide	1.000498
6	Sulphur dioxide	1.000639

V. Conclusion

The reported work provides the review of work proposed by many researchers with their results and sensing parameter (Quality factor, sensitivity, detection limit). These sensors play an important role for sensing and produce a significant data. The PhC structure-based sensor has several advantages as high Quality factor and lower detection limit as compared to other sensors but these sensors also have several drawbacks like fabrication of these compact size sensors, coupling of light or coupling of these designed structures with other structures. As we know that the RI of analyte is dependent on temperature and could have smaller changes for increase and decrease in temperature so the sensing may get affected. The stability of resonant properties against fabrication error is significant. The photonic crystals

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fabrication is limited to nanometre scale. Alongside these drawbacks PhC structure for biochemical and gas sensing is the latest and fasted growing technique for sensing because of optimal design.

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