Efficient Designing and Optimization of Nano-Cavity Photonic-Crystal based Pressure Sensor

Shivam upadhyay[1] Vijay Laxmi Kalyani[2] Chandraprabha Charan[3]
[1,3]M.Tech Scholar [2]Assistant Professor
[1,2,3]Department of Electronics & Communication Engineering
[1,2,3]Govt.Women Engineering College, Ajmer

Abstract— In this paper, we proposed a compact photonic crystal based double hole nano cavity pressure Sensor. The Pressure Sensor is designed by introducing double hole nano-cavity with some side holes in the middle of line defect waveguide. This increases sensor Sensitivity, Quality factor and Resolution factor. Nano Pressure sensor works on the principle of resonance wavelength shift, with the applied pressure. According to the results of proposed design, the shift of resonant wavelength lies in the Optical range. This sensor works in optical S and C band. The sensitivity of silicon membrane based Pressure Sensor is 0.50nm/GPa and its minimum detectable pressure is 0.04 nN. By using plane wave expansion (PWE) method band gap of the structure is evaluated. Finite difference time domain (FDTD) method is utilized for computation of transmission power and field distribution of proposed sensor.

Key words: Nano-Cavity; Physical-Sensor; Optical Sensor; Photonic Crystal(Phc); Refractive Index; Sensitivity(S); Plane Wave Expansion (PWE); Finite Difference Time Domain (FDTD); Photonic Band gap (PBG); Transverse-Magnetic Field etc

I. INTRODUCTION

Photonic crystals (Phc) is a periodic structure, in which periodicity is maintained by periodic arrangement of optical index in one, two or three dimension. This Periodicity of crystal prevents the propagation of certain frequency signal inside the crystal. The main advantage of photonic crystal is the periodic modulation of optical index for controlling photons at the operating wavelength and it also control the duration of the periodic oscillation. Photonic crystal technology is the innovative method for manipulation of guided light [1].

Photonic crystal generally has two types of structures "air holes in slab" and "dielectric rods in air". Both types of structure are used for designing of Phc based devices. Devices which are fabricated using dielectric rods type structure is more out of plane losses due to insufficient vertical confinement by total internal reflection and it shows Transverse magnetic(TM) bandgap. But devices which are based on "air holes in slab" type structure has very low losses and easy in fabrication. For optical sensing applications this type of structure is applicable mostly [2].

Optical sensors have wide range of applications in the field of sensing, due to its ability to detect small changes in temperature, humidity, pressure, chemical composition etc. These sensors are implemented in various smart applications in the field of academic, industry, environmental, health monitoring and biological safety investigation etc. The class of optical sensor is further classified in two categories, Physical sensors and Bio sensors [3], [4].

All Optical sensors are based on the optical resonance phenomena, in which maximum peak occur at resonance wavelength and it will shift if refractive index of sensor is changed due to any external or internal effects. These optical sensors are based on three types of sensing principle: [5], [6]

- Surface Plasmon Resonance (SPR)
- Interferometry
- Optical Resonance

In this paper we design a photonic crystal based pressure sensor with double hole nano cavity resonators. Which couple two waveguides and some small periodically varying cavities are also introduced. All simulation work of pressure sensor is performed by finite difference time domain (FDTD) method and plane wave expansion (PWE) method.

II. PRINCIPLE OF PRESSURE SENSOR

The main sensing scheme usually employed for the photonic crystal (Phc) based sensors are either the intensity reduction of output peak or resonant wavelength shift due to changes in refractive index. The band gap of photonic crystal (Phc) is depend on the refractive-index (η) or dielectric constant (ε) of material, lattice constant (a), and radius-to-lattice constant ratio (r/a). When any external mechanical deformation like pressure, strain, temperature, displacement will apply on the photonic crystal (Phc), the crystal bandgap will changed.

Pressure sensor is also based on optical and electronic properties of material like energy gap and refractive index. In Pressure sensor, Pressure is applied on the surface of sensor and which is distributed in the form of stress on the sensor structure thus band gap of sensor is changed. At different applied pressure the optical coefficients photo elastic, piezoelectric, and permittivity of sensor is also modified which change the refractive index of substrate [7]-[9].

The relation between pressure and refractive index is given by

$$n = n_0 - (c_1 + 2c_2)\,\sigma \quad (1)$$

where c_1 and c_2 are defined as

$$c_1 = n_0^3\,(P_{11} - 2VP_{12}) / (2E) \quad (2)$$

$$c_2 = n_0^3\,(P_{12} - V\,(P_{11}+P_{12})) / (2E) \quad (3)$$

Where E is Young's Modulus constant, V represent Poisson's ratio, and Pij is the strain-optic constant.

In the photonic crystal based pressure sensor, the applied pressure and refractive index of a substrate has linear relationship, as applied pressure is increased the refractive index of sensor is also increased. This increasing refractive index also shifts the resonant wavelength of sensor. It is find that by applying 1GPa pressure on the

sensor, the refractive index of senor is increase with 0.03985 [10].

III. DESIGN AND MODELING

The proposed sensor structure is hexagonal lattice with 'air holes in silicon slab'. The designing process of a sensor is as follows:

A. Selection of Material

Silicon is used as a background material whose refractive index is very high (RI= 3.5). This high RI provides a high RI contrast with air holes. This condition is necessary for getting large band gap.

B. Selection of Lattice Structure

Photonic crystal has two types of lattice structure such as square and hexagonal lattice. In this design we use hexagonal lattice because it has less scattering of light due to its smaller angular (60 degree) geometry.

C. Designing the Unit Cell of the Lattice

The r/a ratio of the lattice is an important parameter of band gap, where, 'a' is lattice constant of structure and r is radius of air hole. For practical implementation of device it is necessary that band gap of designed structure is lies between the optical ranges. For the propagation of light inside the structure some defects are introduced to allow particular range of wavelength. The structure has r/a ratio 0.345 with slab thickness 300nm and lattice constant a=400nm.

D. Adding Defects

For the propagation of light inside the structure, cavity is introduced. It is necessary that designed cavity has high quality factor (Q) and small mode volume(V).The cavity is design by changing or removing the one air hole (point defect or single cavity) or several air holes(line defect or linear waveguide) into the structure[19]. In the proposed structure, line defect is created for the propagation of light and double hole point defect for nano cavity, to achieve high quality factor and sensitivity. These nano cavities are introduced into the middle of line defect and form two waveguides coupled with nano cavity like sensor structure. The vertical confinement of a light is provided by "air holes in slab" type structure. To achieve more quality factor and transmission efficiency, double hole nano cavity structure of sensor is modified by introducing more side holes in both sides of nano cavity. These holes have periodically varying radius0.06, 0.05 and 0.04µm respectively and defected nano cavity radius is R_c = 0.5a. Sketch of pressure sensor based on photonic crystal line defect with double hole nano cavity is shown in Figure 1.

Here three side holes with periodically varying radius are introduced in the double hole nano cavity structure. With three side holes in each side of nano cavity type structure has high quality factor, high transmission power and good sensitivity. Defects of sensor are shown in Figure 2.

For excitation of Gaussian pulse, the transverse magnetic (TM) polarized input optical source of resonance wavelength λ=1.54964 µm is used. The Gaussian pulse enters from the left side of sensor i.e. input port. The resonance wavelength of the cavity is highly sensitive with the refractive index and structure of the sensor. When any external pressure is applied on to the sensor structure its refractive index slightly changed, which is sense by the cavity and thus its resonance wavelength automatically shifts and shows sensitivity towards the applied pressure. This shift in resonance wavelength is detected by the output detector.

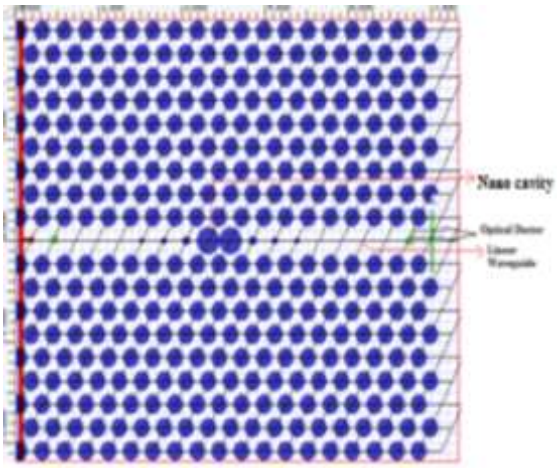

Fig. 1: 2D-PC based Pressure Sensor Layout

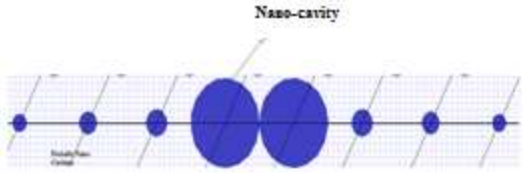

Fig. 2: Double Hole Defect with Periodic side holes

Sr No.	Design Parameters	
	Name of Parameters	***Values***
1.	Radius of the hole(r)	0.1385µm or 138nm
2.	Lattice constant(a)	0.400µm or 40 0nm
3.	Refractive index(holes)	Air (n=1)
4.	Background index	Silicon (n=3.50)
5.	Size	8µm × 6.65 µm
6.	PBG range	1203 nm – 1812 nm
7.	Polarization	TM

Table 1: Parameters and its values used for sensor

Table1. Represent all parameters used in the designing of pressure sensor.

IV. SIMULATION AND RESULTS

For the simulation of Pressure sensor 2D FDTD simulation tool is used .We have also considered the transverse magnetic polarization for the propagation of plane wave inside the sensor. In this type of polarization the magnetic field is normal to the axis of holes.

All results of pressure sensor are demonstrated below:

A. Band-Gap Calculation

Photonic band gap (PBG) of structure, is calculated by using PWE band solver. A broad transverse band gap is found between the ranges from 1203.1710 to 1812.2902 nm. Figure 3 shows the photonic band-gap of pressure sensor.

B. Field Distribution

The 2D and 3D magnetic field distribution of line defect with double hole nano cavity pressure sensor is shown in Figure 4 and 5 respectively.

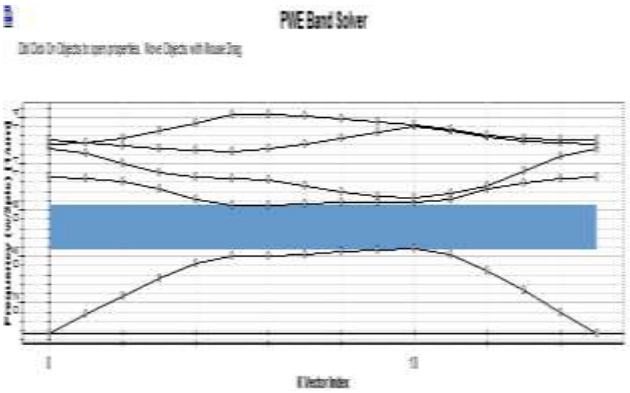

Fig. 3: Photonic Band Gap

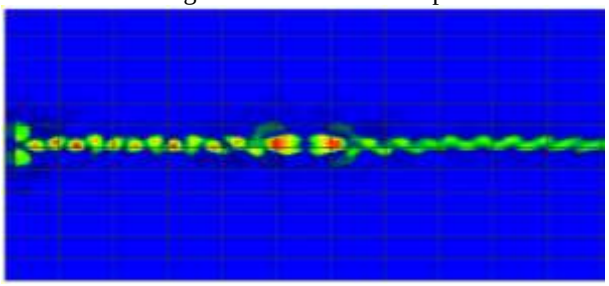

Fig. 4: 2D Magnetic field distribution.

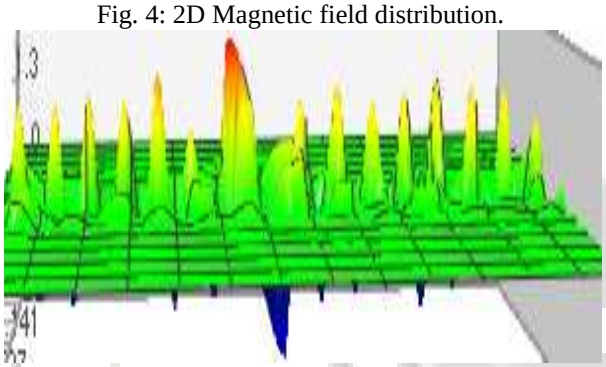

Fig. 5: 3D Magnetic field distribution

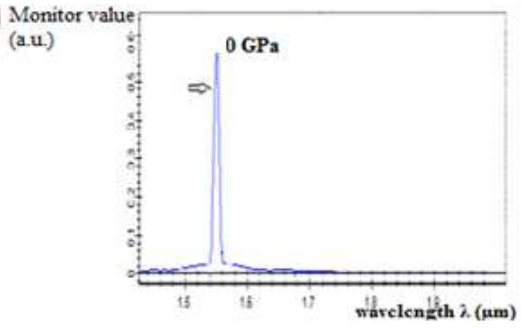

Fig. 6: Normalized transmission spectra of sensor at 0 Gpa pressure.

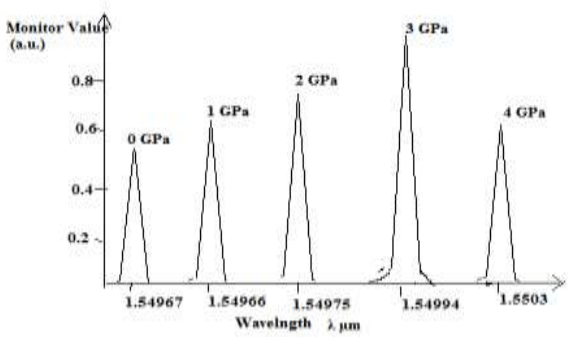

Fig. 7: Normalized transmission spectra of the sensor at different pressure.

			Parameters		
Sr. No.	**Applied pressure (GPa)**	**Effective Refractive Index**	**Resonance Wavelength (μm)**	**Transmission Power (%)**	**Wavelength shift Δλ(nm)**
1.	0 GPa	2.5000	1.54964	58.6	0
2	1 GPa	2.53985	1.54966	64.4	0.02
3.	2 GPa	2.5797	1.54975	67	0.11
4.	3 GPa	2.61955	1.54994	89.6	0.30
5.	4 GPa	2.6594	1.5503	61.3	0.66

Table 2: Analysis of Pressure Sensor

Figure 6 shows the normalized transmission spectrum of sensor when no pressure is applied on the sensor surface i.e.at 0 GPa pressure. In this condition the refractive index of device does not change, thus optical properties of sensor remain same. The resonant wavelength 1.54964 μm and power is 58.6%, respectively.

Figure 7 represents the normalized transmission spectrum of pressure sensor at different pressures such as 1GPa, 2 GPa, 3GPa, 4GPa. In this condition, applied pressure change the refractive index and optical properties of sensor thus resonance wavelength of sensor is shift and sensor shows sensitivity towards the applied pressure.

V. ANALYSIS OF SENSOR

The analysis of sensor parameters like quality factor, sensitivity and minimum detectable pressure are calculated and analyzed. Table 2 represents analysis of pressure sensor. These parameters are as follows:

A. Quality Factor

It is the ratio of resonance frequency to the full width at half maximum (FWHM) of the resonator's Lorentzian response i.e. $\omega_0/\Delta\omega$ [11].The quality factor is represented by 'Q'.

$$Q = \frac{\omega 0}{\Delta\omega}$$

This design of sensor has quality factor of 1549.

B. Sensitivity

Sensitivity is the ratio of minimum shift in resonance wavelength to the change in refractive index $\Delta\lambda/\Delta n$ [11]. It is represented by 'S':

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

In this paper sensitivity of pressure sensor is 0.50 nm/GPa.

C. Minimum Detectable Pressure

Minimum Detectable Pressure is calculated using smallest possible spectral shift and sensitivity of sensor [11].The designed nano pressure sensor detects 0.04 nN minimum pressure.

The observed results show that the refractive index of sensor structure is shifted or increased with the different applied pressure. Thus the resonance wavelength of sensor is also shift. The sensitivity and minimum detectable pressure of the proposed sensor is 0.50 nm/GPa and 0.04 nN, respectively.

VI. CONCLUSION

In this paper, we designed a photonic crystal based pressure sensor for measuring nano pressure. This sensor is based on

linear waveguide with the double hole nano cavity. Pressure sensor is designed using hexagonal structure with the lattice constant a=0.40µm, the radius of the holes r=0.138µm, and the refractive index of slab is 3.50. It is observed that applied pressure, shift the resonant wavelength of the sensor. In the absence of pressure, the resonance wavelength and output power are 1.54964 and 58.6%, respectively. The sensitivity and quality factor of proposed pressure sensor is 0.50 nm/GPa and 1549 respectively. It is capable to detect 0.04 nN minimum pressure. This sensor mainly working in short band (s-band) and conventional band (c-band).

ACKNOWLEDGMENT

The author would like to thank the referees for their construcuctive comments which helped to improve the quality of this paper. I also thank to Vijay Laxmi Kalyani, (Assistant Professor, Department of Electronics and communication, Govt. Mahila Engineering College, Ajmer) for her input on many aspects of this work.

REFERENCES

[1] John D Joannopoulos, ″Photonic Crystals Molding the Flow of Light″, Second Edition, Princeton University of press,2008.
[2] Yasuhide Tsuji ,“ Photonic Crystal Waveguide Based on 2-D Photonic Crystal With Absolute Photonic Band Gap″ IEEE Photonics Technology Letters, vol. 18, November 15, 2014.
[3] I. M. White ,H. Zhu,X. Fan, S. I. Shopova, J. D. Suter, and Y. Sun, “Sensitive optical biosensor for unlabeled target”, Analytica Chimica Acta 620, 2008, PP. 8-26.
[4] R.Monoík, M.Streanský, and E.Sturdík, “Biosensors - classification characterization and new trends”, Acta Chimica Slovaca, Vol. 5, No. 1, 2012.
[5] S. Ghoshal, D. Mitra, and S. Roy, “Biosensors and Biochips for Nonmedical Applications”, Sensors & Transducers Journal, Vol. 113, No. 2, 2010, pp. 1-17.
[6] Y. Liu, and H. W. M. Salemink, “Photonic crystal-based all-optical on-chip sensor”, Optics Express, Vol. 20, No. 18, 2012 ,PP. 19912-1992.
[7] S. Olyaee and A. A. Dehghani, “Nano-Pressure Sensor using High Quality Photonic Crystals Cavity Resonator”, IEEE, IET 8th International Symposium on Communication System ,(CSNDSP 2012), Poznan University of Technology, Poznań, Poland, 18-20 July 2012.
[8] A. A. Dehghani and S. Olyaee, “High resolution and wide dynamic range pressure sensor based on two-dimensional photonic crystals,” Photonic Sensors, vol. 2, 2012, PP. 92-96.
[9] L. A. Shiramin, R. Kheradmand and A. Abbasi, “High-sensitive double-hole defect refractive index sensor based on 2-D photonic crystal”, IEEE Sensor Journal, Vol. 13,No.5,May 2013.
[10] Saeed Olyaee and A. Asghar Dehghani, Nano-Pressure Sensor using High Quality Photonic Crystal Cavity Resonator″, IET International Symposium on Communication Systems 2013.
[11] A. Lavin, R.Casquel ″ Efficient design and optimization of bio-photonic sensing cells (BICELLs) for label free biosensing″, INNBIOD (REF:IPT-2011 -1429-010000) under the Spanish Ministry of Economy and Competitiveness.

