ISSN: 2395-1680 (ONLINE)
DOI: 10.21917/ijme.2017.0075

DESIGN OF 2D PHOTONIC CRYSTAL BASED FORCE SENSOR USING PARALLELOID RING RESONATOR

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Abstract

A 2D photonic crystal based force sensor using paralleloid ring resonator is proposed and designed for sensing the force. An elasto-optic effect method is utilized to analyze the force which persist over photonic crystal. The optical characteristics of paralleloid ring resonator is analyzed and predicted by Finite Difference Time Domain method. A new structure of paralleloid ring resonator is formed by introducing the line defects as waveguide in the design of 2D silicon PC slab in hexagonal lattice with the size of 10µm and 12µm in X and Z direction, respectively. The sensing parameters are observed in the ring resonator which are completely depends on the refractive indices of the material used. Thereby the force can be sensed. The determined sensing parameters such as resonant wavelength is about 1470nm, quality factor is of 145.5 and 100% of transmission efficiency is also achieved.

Keywords:

Photonic Crystal, Force Sensor, Paralleloid Ring Resonator, Sensitivity

1. INTRODUCTION

Photonic crystals are periodic optical nano structure in which refractive index varies periodically. If these refractive indices are sufficiently different, it will give rise to photonic bandgap, which causes prevention of light propagation within a specified range of frequencies spanned by the bandgap. It is possible to manipulate the flow of light within photonic crystal [1]. Force Sensor is defined as a transducer that converts an input mechanical force into an electrical output signal. Force Sensors are also commonly known as Force Transducers. The principle of operation is the elasto-optic effect, in which refractive index variation is induced by mechanical stress. PC structure under various applied forces. These deformations are applied in FDTD simulations to obtain the sensor characteristics for various applied forces. There are some of the attractive features in sensor like sensitivity, dynamic range accuracy reliability, etc. In optical sensing two approaches have been utilized namely, the impact of resonant wavelength shift scheme and intensity variation scheme. The intensity variation leads to higher sensitivity.

The applications of photonic crystal based sensors are as follows, chemical sensing, force and strain sensing [2], refractive index and gas sensing [3], dengue virus detection [4], pressure sensing [5], aqueous environment [6] and biosensing [7]. Photonic crystal based devices can also be designed for several applications such as optic filters [8], optical demultiplexers [9], optical switches [10], optical logic gates [11], polarization converters etc [12].

In 2008, Lee et al. have proposed the design and modeling of nanomechanical sensor for the analysis of pressure from 1Mpa-2Mpa, where the quality factor is of 1000, also the resonant wavelength shift occurred from 1500-1700nm with the intensity of 0.8 [13]. In 2009, Xiang and Lee have designed the nano photonic sensor based on microcantilever for chemical analysis, where the force is about 500nN and its quality factor is of 1500. Here the resonant wavelength got shifted from 1590-1605nm with the intensity of 0.18 [14]. Microcantilever sensor have proposed by Xiang et al. for the analysis of force is of 100nN. The quality factor for water and air is of 1100 and 5500 respectively. The resonant wavelength shift obtained from the 1440-1446nm with the minimum intensity of 0.14 [15]. In 2009, Lee and Thillaigovindan have proposed and designed optical nanomechanical sensor for analysis of force 100nN. The quality factor is of 1000 along with the resonant shift obtained from 1440-1446nm with the minimum intensity of 0.5 [16].

Hsiao and Lee in 2010 have predicted the computational study of PC nano-ring resonator for biochemical sensing. Two hole coupling distance and 5 hole ring radius is utilized to obtain the quality factor 2500 along with the shift in the resonant wavelength about 1540-1550nm. Here the intensity achieved is of 0.07 [17]. In 2011, silicon microcantilever sensors have designed and proposed by Mai et al. the force sensed is of 62.5nN. The obtained quality factor is 3896 with the shift of 1404-1406nm of resonant wavelength with the intensity of 0.12 [18]. Li et al. in 2011 have proposed NEMS cantilever using dual nano-ring resonator to sense the force is of 76nN with the quality factor of 876 along with the resonant wavelength shift of 1553-1556nm. The minimum intensity obtained is of 0.06 [19]. In 2011, Li et al. had proposed and explained about cantilever sensors using a hexagonal dual nano-ring based channel drop filter. Here the force sensed is of 76nN of quality factor is 3470 with the intensity of 0.44, the resonant wavelength shift occurred is from 1553-1560nm [20]. The stress sensor with high sensitivity in double directions based on shoulder coupled aslant nano cavity. The force sensed in both horizontal and vertical direction are of 58nN and 44nN respectively. The quality factor is of 3000 with resonant wavelength of 1530-1560nm. The intensity obtained is of 0.8 [20]. In 2016, Sreenivasulu et al. [22] have proposed force sensor to measure sub-micro newton forces over a wide range. The force sensed here is of 100nN with the quality factor of 10,000. The resonant wavelength shift occurred from 1550-1560nm with the intensity of 0.16 [22].

Generally, when the light signal is passed inside the periodic structure, a certain range of wavelength signal will be passed and some range of signal is reflected back to input source. The range of wavelength where the light signal is reflected back to the source is termed as Photonic Band Gap. The PBG is broken is completely by introducing the defects in the periodic structure. The performance of the PC based sensor is evaluated by incorporating the defects.

Hence obviously, ultimate aim is to overcome the issues in the previous literatures and achieve higher order of sensing parameters. A 2D photonic crystal based force sensor is designed using paralleloid ring resonator in hexagonal lattice for sensing the force. In the above literatures, the impact of resonant wavelength shift scheme is obtained. In this paper, the intensity variation scheme is achieved.

Also the maximum normalized intensity is achieved. The force to be sensed is in the range of 0-130µN. The higher order of sensing parameters can be achieved by this paralleloid ring resonator such as resonant wavelength is in the range of 1440-1500nm, quality factor is of 145.5, 100% of transmission efficiency. Hence the higher orders of sensing parameters are achieved in this paper which is greater than literatures reported before [13-22].

In this attempt, Plane Wave Expansion (PWE) method is used to analyze the propagation modes and Photonic Band Gap of the periodic and non-periodic structures. As the PWE method is not predicting output spectra accurately, Two Dimensional Finite Difference Time Domain (FDTD) method is employed to get the normalized output spectra of the proposed sensor. Rsoft-Bandsolve and Fullwave is employed to get PBG and Normalized output spectra.

The rest of the paper is organized as follows, the proposed design is explained in section 2, simulation results and discussions are reported in section 3 and section 4 concludes the paper.

2. NUMERICAL ANALYSIS

One of the important property called as Photonic Band Gap exhibited by photonic crystals. The transmission of electromagnetic waves in certain range of frequencies are prohibited, i.e. there is no propagation of light over some order of wavelengths. It can be termed as photonic band gap. Defect mechanism can be introduced for the manipulation of light propagation. The line defect in the ring resonator acts as waveguide. Thereby the sensitivity can be enhanced. In the ring resonator, the normalized intensity can be altered as the refractive index gets varied. The photonic crystal functions as sensor can be proved by solving Maxwell's electromagnetic equation [23].

$$\nabla\times\left(\frac{1}{\in}\nabla\times H\right)=\left(\frac{\omega}{c}\right)^2 H \tag{1}$$

In Eq.(1), H is the magnetic field and C is the speed of light. Also ε is the permittivity (dielectric function $\varepsilon=\eta^2$ or $\eta=\sqrt{\varepsilon}$ where η is the refractive index), ω is the frequency of resonance. It is observed that when the dielectric function changes the frequency also changes. From the Eq.(1) it is noticed that dielectric function ε is inversely proportional to frequency ω. The sensing performances of the structure can be analyzed by the Eq.(2) [21].

$$L_{eff}=\frac{Q\lambda}{2\pi\eta} \tag{2}$$

In Eq.(2), L_{eff} is the effective interaction length, Q is the resonator quality factor, λ is the resonant wavelength, η is the refractive index of ring resonator.

3. PROPOSED DESIGN

3.1 PHOTONIC BAND GAP

The Fig.1 depicts the band diagram of hexagonal lattice without introducing any defects. The defects are nothing but introducing the alteration in the structural parameters such as lattice constant, radius of rod and dielectric constant.

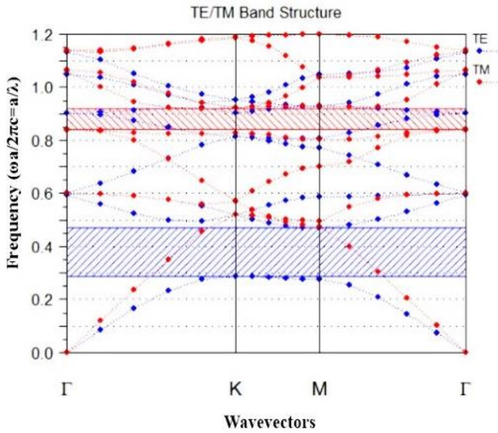


Fig.1. Band Diagram of Proposed Device

The band diagram has a PBG of TE and TM modes at different wavelength ranges which is listed in the Table.1. PBG of TE and TM modes can be showed by blue and red coloured region respectively. We have considered the wavelength range from 1125nm to 1725nm as it belongs to third window since it is highly efficient in the communication systems.

The horizontal and vertical axes in the band diagram represent the wavevector and normalized frequency, respectively. The wavevector is calculated in the Brillouin zone, which is equal to the entire periodic structure. The normalized frequency of the PC structure is $\omega_a/2\pi c = a/\lambda$, where, ω is the angular frequency, a is the lattice constant, c is the velocity of light in free space and λ is the free space wavelength.

Table.1. Frequency and Wavelength from PBG

Types of PBG	Frequency (a/λ)	Wavelength (nm)
TE	0.480-0.313	1125-1725
TM	0.954-0.865	566-624

3.2 PC BASED FORCE SENSOR

The Fig.2 depicts the designed photonic crystal based force sensor using paralleloid ring resonator which consists of the hexagonal array of circular silicon rods placed in a background of air. In the hexagonal lattice, the total number of rods in X and Z direction are 21 and 21, respectively. The proposed sensor consists of two optical waveguides namely bus waveguide and dropping waveguide. The bus waveguide acts as an input port placed at one end whereas dropping waveguide acts as an output port at another end.

Bi-periodicity is introducing at output port, it is nothing but reducing the radius of rods in specific manner, such as it having hexagonal form in which radius of centre rod is 55nm, whereas the outer rods radii is about 90nm. Paralleloid ring resonator is placed at the centre of design whose radius is about 110nm. The distance between the two rod is about 540nm, it is also called as lattice constant denoted by *a* and the dielectric constant of Si rod is 14.5 (refractive index = 3.82). The Fig.3 shows 3D view of proposed sensor. The size of sensor is about 11.4µm×9.8µm. The simulation parameters of the sensor are listed in Table.2.

In PC based sensor, there are two schemes are reported namely wavelength shift scheme and intensity reduction scheme. In the first scheme, the wavelength is shifted from one value to another while changing the sensing parameters; the intensity is varied in the second scheme. The refractive index is varied while changing the applied force which directly changes the output intensity of the proposed sensor. The applied force, refractive index, resonant wavelength and the respective intensity is stored in the system. In real time situations, when the force is applied, the effective refractive index is varied which changes the output intensity. By knowing the value of intensity and resonant wavelength from the system, one can easily identify the applied force.

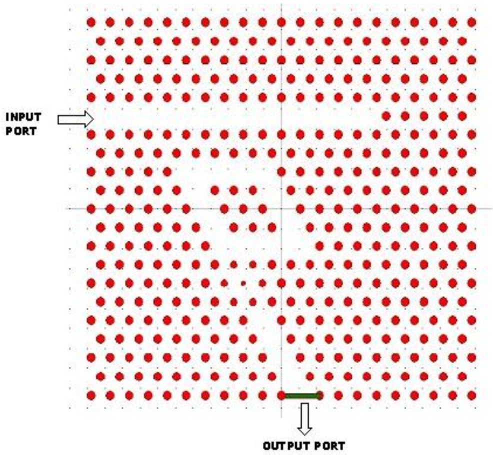


Fig.2. Schematic Representation of Proposed Force Sensor

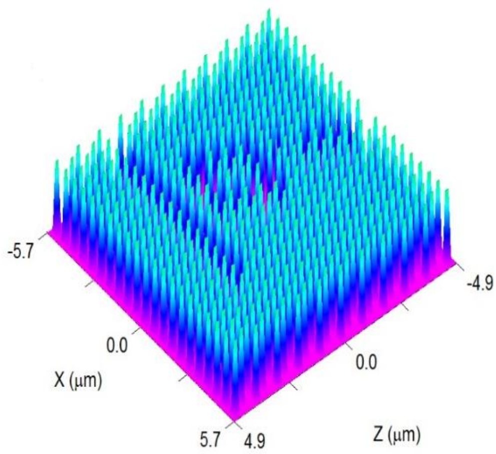


Fig.3. 3D View of Proposed Force Sensor

When the light is propagating from bus waveguide (input port), through the paralleloid ring resonator of sensor, there is some interactions of light with mechanically deformed photonic crystals. Due to the changes in the refractive index of material there is shift in the normalized intensity. Correspondingly existence of force can be noticed. Thereby the force can be sensed finally. These can be observed at dropping waveguide (output port). The schematic representation of sensing mechanism is shown in Fig.4 consists of several components such as optical source, photonic crystal based force sensor, photo detector, signal processing unit and display.

Table.2. Simulation Parameters of Sensors

Design Parameters	Values
Configuration	Rod in air
Rod shape	Circular
Lattice structure	Hexagonal
Lattice constant	0.54µm
Radius of rod	0.11µm
Refractive index of rod	3.82
Dielectric constant of Si rod	14.5

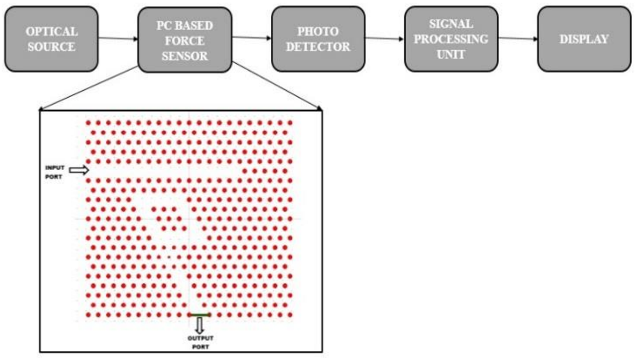


Fig.4. Schematic Structure of Force Sensor

Optical source is the one by which the optical light is produced then reached in to the sensor where light is getting propagated through the photonic crystal which is got deformed mechanically. Photo detector is used to convert electrical signal into optical signal. Then the output is processed in the signal processing unit. The processing includes filtering, modulation, demodulation, phase shifting, frequency conversion etc. Based on desired output the functions may be carried out in it. Finally output will be displayed in the display.

4. SIMULATION RESULTS AND DISCUSSION

The shift in refractive index of material leads to the shift in the normalized intensity. According to that, there is changes in the range of force, whereas the resonant wavelength is remain constant. In such a way the sensor has to be designed. So that the force can be sensed. The normalized transmission spectrum of the sensor is shown in Fig.5. From that, obtained resonant wavelength, quality factor and normalized intensity is about 1470nm, 126.7 and 100%, respectively. The light signal is launched into the input port. The output signal power reaches the power monitor which is positioned at the output port is normalized by the input signal power.

The electric field distribution of the proposed sensor at 'ON' resonance and 'OFF' resonance is representing in Fig.6(a) and Fig.6(b), respectively. It is clear that the signal couples in to the sensor at the resonance wavelength. The signals getting couples only at and above the resonance wavelength. This condition can be termed as ON resonance is about 1470nm. When the signal is not able to couple below the resonant wavelength is about at 1300nm then that condition is called OFF resonance.

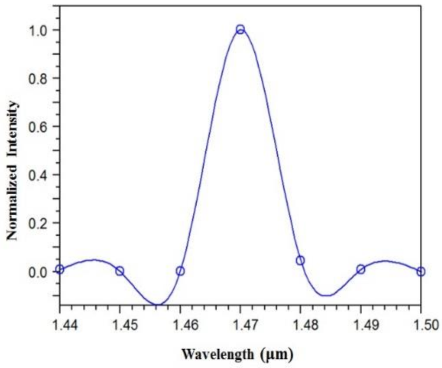
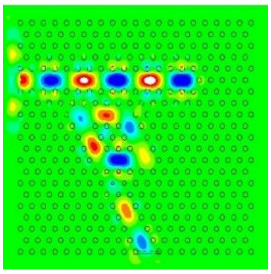
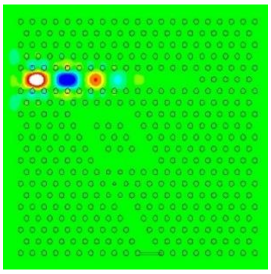


Fig.5. Normalized Transmission Spectrum of the Proposed Sensor



(a) λ = 1560nm



(b) λ = 1300nm

Fig.6. Schematic Representation of Field Distribution of sensor at (a) ON resonance (b) OFF resonance

The normalized output spectrum of proposed sensor is depicted in Fig.7. It is noticed that when the value of refractive index gets increase then the value of normalized intensity gets decreases. It leads to increase in the value of forces which can be sensed. Since the resonant wavelength is remain unchanged. Force about 0-50µN is sensed in it with span of 5µN. The refractive index variation is from 2.8200 to 2.8259. Here the shift in the intensity decreases from 100% to 92%. The resonant wavelength is about 1470nm. It is remain constant over any changes in refractive index of sensor.

From Fig.8, it is clear that the force is sensed about 0-130µN with span of 10µN with the refractive index variation from 2.8200 to 2.8354. There is linear decrease in normalized intensity from 100% to 15%. Also it is clear that when there is decrease in the intensity, the value of force sensed here is getting increased. The resonant wavelength is 1470nm. Here also it is remain constant. In Fig.9, the force is sensed about 0-100µN with span of 25µN, correspondingly the refractive index variation is from 2.8200 to 2.8318. Hence there is shift in the normalized intensity in decreasing order.

The intensity decreasing from 100% to 45%. In Fig.7, the resonant wavelength is remain constant, it is about 1470nm. From these figures it is clearly understood that when there is increase in the value of refractive indices then there is correspondingly decrease in the intensities of sensor. By which the different values of force can be sensed. Here the intensity shift mechanism is obtained thereby it is clear that the resonant wavelength is remain unchanged.

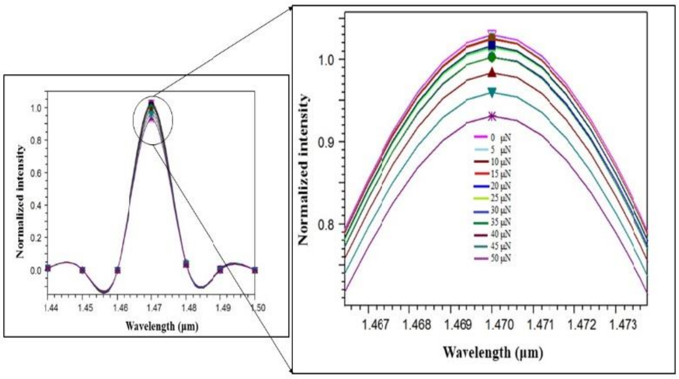


Fig.7. Normalized Transmission Spectrum of the Proposed Sensor of Force (0-50µN)

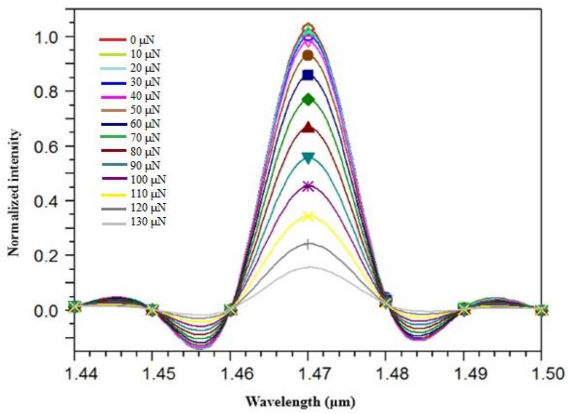


Fig.8. Normalized Transmission Spectrum of the Proposed Sensor of Force (0-130µN)

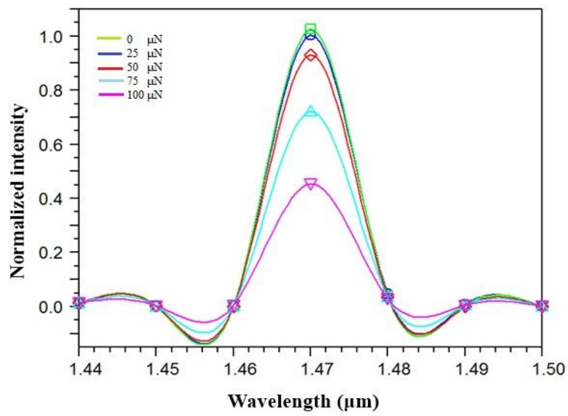


Fig.9. Normalized Transmission Spectrum of the Proposed Sensor of Force (0-100µN)

From the Table.3, it is easy to understand the functions and performances of sensor designed with the specific parameters. The parameters are refractive index, force, quality factor, output power. From the above table, the sensed force value is about 0-50µN. Here, the obtained values of resonant wavelength, quality factor and output power are 1470nm, 127.8 and 100% respectively. Also the refractive index variation is from 2.8200 to 2.8259.

From the Table.4, the sensed force value is about 0-130µN. The parameters to be analyzed are refractive index, force, quality factor, output power. Here the obtained values of resonant wavelength, quality factor and output power are 1470nm, 133.6 and 100% respectively. Also the refractive index variation is from 2.8200 to 2.8354.

From the Table.5, the above table, the sensed force value is about 0-100µN. The parameters to be analyzed are refractive index, force, quality factor, output power. Here the obtained values of resonant wavelength, quality factor and output power are 1470nm, 145.5 and 100% respectively. Also, the refractive index variation is from 2.8200 to 2.8318.

Table.3. Refractive Index, Quality Factor and Transmission Efficiency of the Sensor at Different Force Ranges from (0-50µN)

Refractive Index	**Force (µN)**	**Quality Factor**	**Transmitted Power (%)**
2.8200	0	126.7	100
2.8205	5	127.8	100
2.8211	10	126.7	100
2.8217	15	118.5	100
2.8223	20	120.4	100
2.8229	25	142.7	100
2.8235	30	118.5	100
2.8241	35	125.6	99
2.8247	40	133.6	98
2.8253	45	123.5	95
2.8259	50	140	92

Table.4. Refractive Index, Quality Factor and Transmission Efficiency of the Sensor at Different Force Ranges from (0-130µN)

Refractive Index	**Force (µN)**	**Quality Factor**	**Transmitted Power (%)**
2.8200	0	126.7	100
2.8211	10	126.7	100
2.8223	20	120.4	100
2.8235	30	118.5	100
2.8247	40	133.6	98
2.8259	50	140	92
2.8271	60	126.7	85
2.8283	70	123.5	76
2.8295	80	125.6	66
2.8307	90	116.6	55
2.8318	100	144.1	45
2.8330	110	125.6	34
2.8342	120	120	24
2.8354	130	114.8	15

Table.5. Refractive Index, Quality Factor and Transmission Efficiency of the Sensor at Different Force Ranges from (0-100µN)

Refractive Index	**Force (µN)**	**Quality Factor**	**Transmitted Power (%)**
2.8200	0	126.7	100
2.8229	25	142.7	100
2.8259	50	140	92
2.8289	75	145.5	71
2.8318	100	144.1	45

5. CONCLUSION

The two dimensional photonic crystal based force sensor is designed and its sensing characteristics are analyzed. The sensor is designed using two dimensional photonic crystals with the hexagonal lattice of circular rod surrounded by air. The sensor is designed with the refractive index range from 2.8200 to 2.8354, which is used for analysis of force along with sensing parameters such as the resonance wavelength, quality factor and output power of the sensor are 1470nm, 145.5 and 100% respectively. Also the intensity variation from 100% to 15% is obtained. The designed sensor is highly sensitive to refractive index. By the variation in the refractive index value, there is shift in the normalized intensity. Hence the sensor is designed in such a way to obtain the desired output.

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