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High Sensitive Refractive Index Sensor Based on 2D-Photonic Crystal

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***Abstract*— In this paper, we demonstrated a Physical Refractive Index Sensor. The Physical Refractive Index Sensor is consisted of a nano-cavity line defect and two waveguides. The nano cavity defect placed in middle of the structure with two end waveguides in both sides. This refractive Index sensor senses the changes in the refractive index of the material and shifts its operating wavelength according to the changes. Due to the changes in refractive index of rods, the resonant wavelength of sensor is shifted. According to the results, the resonant wavelength shift in the Optical range, with respect to the refractive index variations. The quality factor and sensitivity of sensor are respectively obtained. By using plane wave expansion (PWE) method band gap of the structure have been evaluated. Finite difference time domain (FDTD) method has also been used to compute the transmission power, electric field distribution and magnetic field distribution properties of the system.**

Keywords*— Nano-Cavity; Resonator; Physical-Sensor; Optical Sensor; Photonic Crystal; Refractive Index; Sensitivity; Plane Wave Expansion (PWE); Finite Difference Time Domain (FDTD); Photonic Band gap (PBG); Transverse Electric Field; Transverse-Magnetic Field etc.

I. INTRODUCTION

In 1887 Lord Rayleigh was first who gives the propagation of electromagnetic wave principle in periodic media structure. After this in 1987 Eli Yablonovitch and Sajeev John propose their research work in the field of Photonic Crystal. They also predict the existence of the Photonic band-gap as well as spontaneous emission and localization of light with in defects. Photonic Crystal is a material which controls the light guiding properties. Photonic Crystal is a periodic structure with different dielectric constant. [1]

In recent years various devices based on Photonic Crystal material is designed and fabricated e.g. Sensors, Splitters, Filters, and Multiplexers etc. Optical Sensors based on a Photonic principle are also having a wide range of applications in the field of health care, defense, security, automotive, aerospace, environment and food quality control.[1],[2]

Sensor is a device which senses the physical and biological changes and responds according to them. Various types of electronic sensors and optical sensors are designed. But now a day the demand of optical sensors are increased more rapidly as compare to electronic sensors. Sensors based on optics have a lot of attention over time due to their high degree of sensing capability or high sensitivity to detect small changes in temperature, humidity, pressure, chemical composition etc. Photonic Crystal based Sensor having different architectures like Ring Resonator, Surface Plasmon Resonator, Micro-disks, and Micro-spheres etc. [3]-[6]. A complete sensing application of Photonic Sensors is divided into two broad categories:

A. Physical Sensors

Optical Sensors which measure the physical parameters such as temperature, curvature, displacement, torsion, pressure, refractive index, electric-field and vibration etc are come under this category. These types of sensors having application in the field of health monitoring system.

Various types of Physical sensors are designed like Curvature/Bend Sensor, Displacement / Strain Sensor, Electric and Magnetic field Sensor, Pressure Sensor, Temperature Sensor, Torsion/Twist Sensor, Refractive Index Sensor, Vibration Sensor, Multi Parameter Sensor etc.[6],[7]

B. Bio-Chemical Sensors

Photonic Crystal can also be used for the sensing of chemical and biological samples. In the field of biomedical system the optical sensor is very advantageous because of their special features like small size, flexibility, remote capability and electrically passive nature. It will not create any risk to the patients because there are no electrical connections to their body. Gas sensor, Molecular sensor, Humidity and PH sensor, DNA sensor are the example of bio-chemical sensors. [7]- [11].

II. DESIGN AND MODELLING

The Refractive Index sensor based on two-dimensional Photonic Crystal is designed by using of square lattice structure. The Silicon circular rods are placed in air background. This type of structure is used for reducing the scattering loss and for effectively controlling the transverse electric (TE) mode propagation. [12] In the square lattice structure, the number of rods in X direction is 17 and in Z directions are 21. The distance between the two adjacent rods is lattice constant (a). In this design lattice constant is 540 nm. The radius of the silicon rod is 0.1 µm or 100 nm, and the dielectric constant of the Si rod is 11.9716 (refractive index = 3.46).Here rods in air type structure is used.

In the Fig. 1 the band diagram of Sensor structure is shown, which gives the Photonic Band Gap for Transverse Electric modes. Electric field of these modes is parallel to the silicon rod axis. The complete structure having two band gaps. The first PBG is in the range between the wavelength 1240 nm and 1831 nm, and the second PBG is from 716 nm and 738 nm. Gaussian continuous wave is used as an input wave of this structure and its wavelength is exactly center wavelength of this PBG wavelength range. The frequency of the Photonic Crystal structure is given by $\omega a/2\pi c = a/\lambda$, where ω represent angular frequency, a represent lattice constant, c represent velocity of light in the free space, and λ represent the free space wavelength. [13] The Plane wave expansion (PWE) method is used, to estimate the band gap and propagation modes of the PC structure without and with defects.

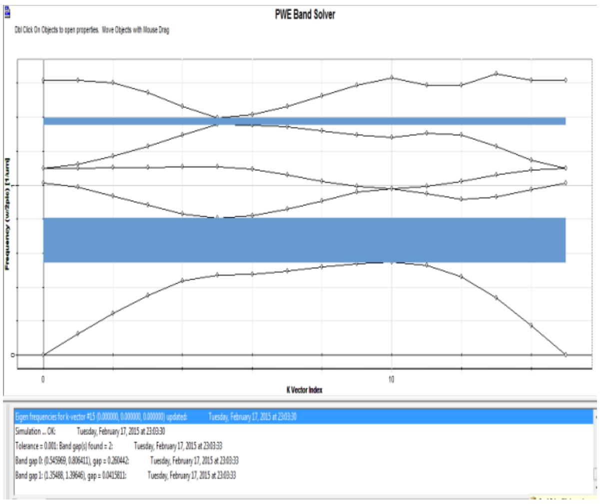

Fig. 1. TE PBG of Refractive Index Sensor.

The simulation parameters of the Refractive Index sensor are listed in Table 1.

TABLE I. PARAMETERS AND ITS VALUES USED FOR SENSOR

Sr No.	**Design Parameters**	
	Name of Parameters	***Values***
1.	Radius of the rod(r)	0.1 µm or 100nm
2.	Lattice constant(a)	0.540µm or 540 nm
3.	Refractive index(rod)	Silicon (n=3.46)
4.	Background index	Air (n=1)
5.	Size	12.4 µm × 9.2 µm
6.	PBG range	1240 nm – 1831 nm
7.	Polarization	TE

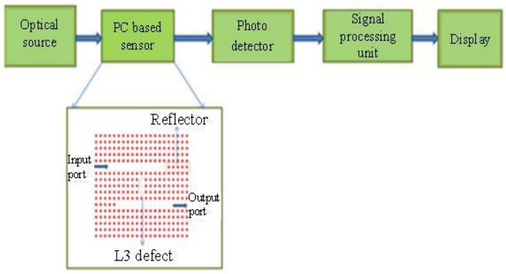

Fig. 2. Block diagram of the PC based sensor [28].

Fig. 2 shows the block diagram representation of practical implementation of refractive index sensor to sense the pressure using the 2D-PC. In this optical source act as a transducer which convert electrical energy in the foam of optics and emits the optical signal which passes to the PC based Refractive Index sensor. This sensor is used to manipulate light with respect to the refractive index variation of the pressure. Then, the manipulated light passes to the photo detector which is also act as an inverse transducer convert optical signal into electrical. Signal processing units map the sensed quantity in the readable form with the help of the look-up table which is displayed in the display board. This type of refractive index sensors can be converted into pressure, temperature etc type of sensor. [14]- [18]

A. Sensing principle

Refractive index sensor is based on the refractive index property of Photonic Crystal Material. The applied changes are based on the electronic and optical properties of the material such as the energy gap. When a refractive index of a material is changed, the Photonic band gap is also changed, which shift the resonance wavelength. When optical coefficients such as photo elastic, piezoelectric, and permittivity of structure is changes then refractive index of Si rods are also modified. In Photonic Crystal structure, the Band Gap is mainly dependent on three parameters that is refractive index, lattice constant, and radius to lattice constant ratio *r*/*a*. In the PC waveguide coupled to the resonator output, the spectrum of the waveguide changes with different refractive index. The resonant wavelength of the resonator is dependent on the geometrical shape of the defect that foams the cavity. By applying certain shift into the refractive index of the structure, the resonant wavelength of the sensor automatically shift and intensity variation of the resonator can be measured. [19]- [28]

Fig. 3 shows that the photonic crystal based refractive index sensor structure has two waveguides in the *X* direction, and L3 defect is positioned between them. The input Gaussian signal is applied to the port marked “input port” from the left side of the waveguide, and the output is detected using a power monitor at the output port marked “output port” from the right side of the waveguide. The waveguide is formed by introducing line defects whereas the L3 defect is formed by modifying the radius of three rods by 0.03 µm. To prevent scattering of light inside the sensor structure the radius of rods near the waveguide input and output port is also changed to 0.12 µm. To enhance the output power of sensor, reflector is positioned at each corner of the waveguide which provide reflection of propagated light. The defects broken, the completeness of the PBG structure and so that guided modes (even and odd modes) propagate inside the Photonic Band Gap region. By controlling the defect size and shape, the guided modes are regulated. Fig. 4 shows the 3D view of the PC based refractive index sensor structure. The size of the pressure sensor is 12 µm × 9.2 µm.

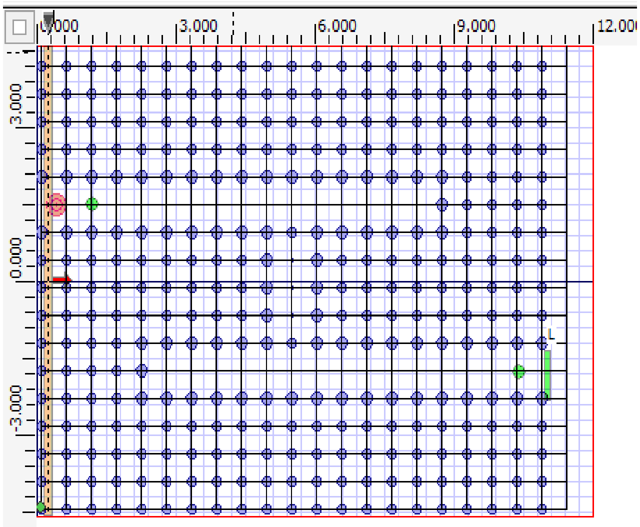

Fig. 3. 2D-PC based Refractive Index Sensor Layout.

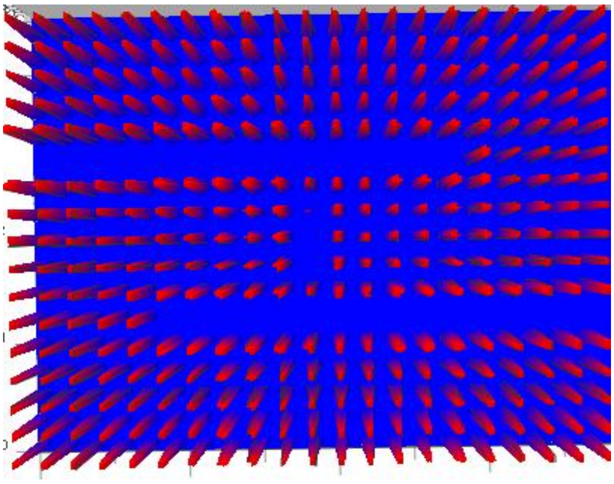

Fig. 4. 3D view of the PC based refractive index sensor structure.

III. Simulation Results

The performance of the sensor such as the sensitivity and dynamic range is investigated by using of the 2D finite-difference time-domain (FDTD) method. A Gaussian modulated continuous light signal is launched at the input port of the waveguide with the wavelength of 1.5355µm.At this wavelength very small amount of losses occurs inside the sensor. So it is considered as a resonance wavelength of this structure. The output signal is recorded at the output port. The output port is normalized by the input signal power i.e., the output power is the normalized output power. The obtained output response is used to analyze the resonant wavelength, quality factor, and output power. [28]

Fig. 5 shows the normalized transmission spectrum of the refractive index sensor when no refractive index change is applied to the sensor. In the absence of the refractive index changes, the resonant wavelength of the sensor is 15355 nm respectively.

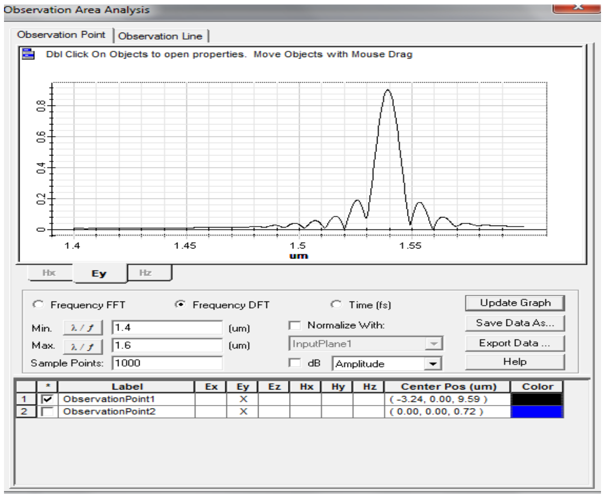

Fig. 5. The normalized transmission spectrum of the sensor with no refractive index change.

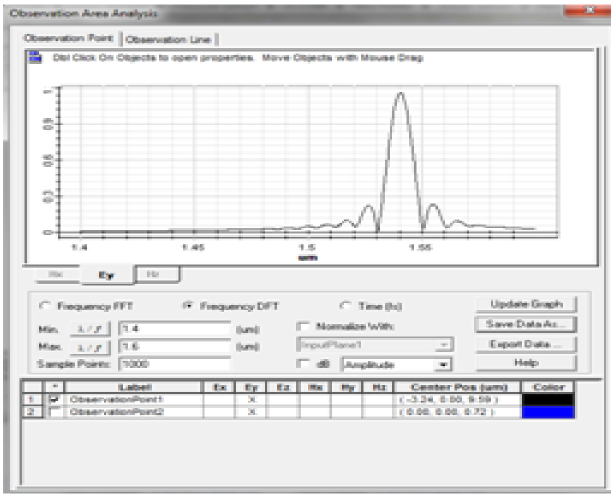

Fig. 6. The normalized output spectra of the sensor with the changing refractive index (n=3.5085).

Fig. 6 shows the normalized output spectra of the sensor at the changing refractive index with the refractive index resolution factor Δn=0.03985.when refractive index is 3.5085.The observed results shows that the resonant wavelength of the structure shifts to the longer wavelength while shifting the refractive index. The sensor is based on the resonant wavelength shift scheme with the changing in refractive index. The applied shifting in refractive index, resonant wavelength, and output power of the sensor are given in the table2.

TABLE II. ANALYSIS OF RESONANT WAVELENGTH OF THE SENSOR WITH REFRACTIVE INDEX RESOLUTION FACTOR ΔN = 0.03985.

Sr No.	**Parameters**		
	Refractive Index	***Resonance Wavelength(μm)***	***Output Power (%)***
1.	3.4600	1.5355	89.8
2.	3.5085	1.5396	90

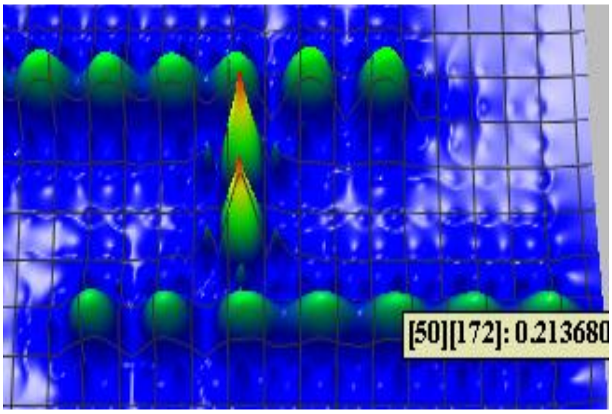

Fig. 7. Electric field distribution of the sensor.

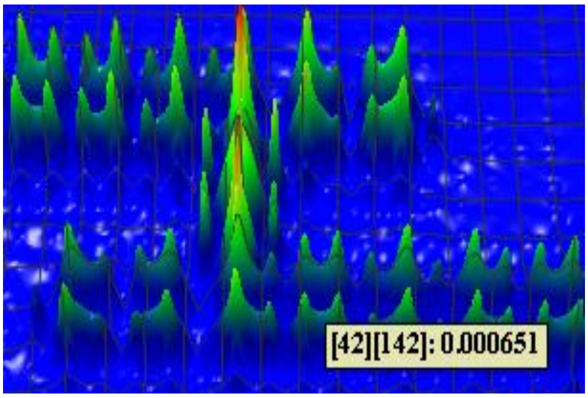

Fig. 8. Magnetic field distribution of the sensor.

Fig. 7 and Fig. 8 represent the electric filed and magnetic field pattern of the sensor at 1.5355 μm respectively. At the resonant wavelength λ=1.5355 μm, the electric field of the waveguide is fully coupled in the L3 cavity and reaches at the output port.

IV. FUTURE SCOPE

Refractive Index Sensor is further implemented as a Pressure Sensor and Force Sensor, which sense the applied pressure or force and having changes in Photonic Band Gap of the structure and this makes shifting in the resonance wavelength of the sensor. It also used as an On/Off resonator.

V. CONCLUSION

We simulat a refractive index sensor based on two waveguide connected with each other by using a line defect.And line defect is created by small changes in the radius of three silicon rods and calculate.This sensor is designed using a square structure with the lattice constant a=0.54μm, the radius of the rod r=0.1μm, and the refractive index of rods are 3.46. It is noticed that the resonant wavelength of the sensor is shifted to the longer wavelength while increasing the refractive index. In the absence of changes, the resonance wavelength and output power are 1.5355μm, 89.8%, respectively. The size of the sensor is 12 μm×9.2 μm which is highly suitable for the sensing applications.

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