Recent Developments On Photonic Crystals Based Sensors- A Review

Mr. Pankaj[1], Dr. Divya Dhawan[2].
[1]M.Tech. Student (Electronics), Dept. of Electronics &Communication Engineering, Punjab Engineering College (Deemed To Be University), Chandigarh, India.
[2]Associate Professor, Dept. of Electronics & Communication Engineering, Punjab Engineering College (Deemed To Be University), Chandigarh India.
[1]pankaj91460@gmail.com, [2]divyadhawan@pec.ac.in

Abstract: In photonic devices, photonic crystals is a concept that provides and easy way to study the optical properties of light and molding the flow of light as desired. Photonic crystals are fabricated artificially with the lattice constant of the order of 0.5 micrometer which is 1000 times larger than lattice constant of atomic crystals and 100 times smaller than the diameter of human hair. Fabrication is done by using techniques like microlithography that further includes e-beam lithography & X-ray lithography. Photonic crystals have possible applications such as biological sensors, narrowing the spectral width of LASERs, temperature and pressure sensing etc. Photonic crystals based sensors can be employed in medical field to detect deadly diseases like cancer, tumor etc. Recent research has been reviewed with intention to provide the idea of photonic crystals and how they are taking control over other conventional techniques.
Keywords: Finite-difference time-domain (FDTD), photonic band gap, photonic crystals, photonic sensors.

I. INTRODUCTION

Photonics is an emerging technology in today's era. Photonics is a physical science of light generation, detection and manipulation through signal processing, sensing and amplification. Higher bandwidth, faster data processing and transfer, energy saving, less prone to interferences, cost and dimension reduction are key benefits that are yielded with the use of photonic devices. Devices that work with photonics are known as photonic devices like LASERs, LEDs, photo-detectors etc. These are the devices that work with manipulation of photonic properties of photons. For the sake of controlling the properties of light completely, the major challenge that general photonic devices face is miniaturizing of devices. This problem can be solved by using the concept of photonic crystals. Photonic crystals can be designed with various geometries along with multiple defects in desired dimension (1D, 2D, 3D) as per the target application.

One dimension photonic crystals offer periodic dielectric media variations only in one direction as shown in Fig.1(a). They have applications like anti-reflection mirrors as central rear mirror in vehicles, transparent electrodes that can be used in medical applications for patient's pulse monitoring and also in transparent TV screens. Although applications of one dimensional photonic crystals are limited and cannot be used in sensor applications because sensors requires confinement of light and that can be achieved using two dimensional (2D) and three dimensional (3D) photonic crystals. In one dimension photonic crystals, periodic dielectric media variations are offered in two directions to the flow of light as shown in Fig.1(b). This type of photonic crystals are widely used with different defects (line defects or point defects in various combinations) in many applications like nano-cavity coupled photonic crystal waveguide as highly sensitive platform for cancer detection, four channel label free photonic crystal biosensor using nano-cavity resonators, optimization of photonic crystal cavity for chemical sensing and many more. Two dimension photonic crystals provide light confinement facility from two directions and hence this type has applications in sensors like bio-sensors and chemical sensors. Three dimension photonic crystals offer dielectric media variations in all three dimensions (x, y and z) as shown in Fig.1.1(c). In comparison to other two types of photonic crystals, though the 3D photonic crystals are the complex ones, researchers are fancied by the 3D photonic crystals because it gives the liberty of localizing light at the centre of the photonic crystals.

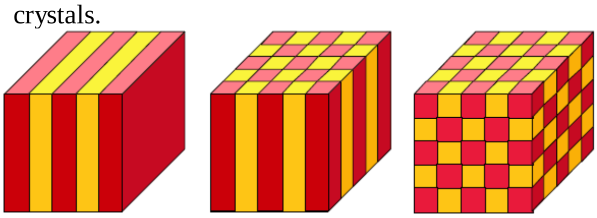
(a) (b) (c)

Fig.1. Periodicity of photonic crystals (a) periodicity in1D, (b)periodicity in 2D, (c) periodicity in 3D.

In photonic crystals, periodic dielectric media variations are created that further induces a band of frequencies which is forbidden from entering the photonic crystal. This forbidden band of frequencies is known photonic band gap which is similar to electronic band gap in semiconductor technology. Photonic band gap is an important aspect in photonic crystals which is forbidden to propagate through the crystal structure. By introducing certain defects in crystal structure, light of a certain frequency from photonic band gap is made to travel through the crystal structure. Various parameters are studied like transmission spectra, resonant wavelength shifts with refractive index variations in defects etc. Moreover, to study the light propagation through the photonic crystals, different techniques are used that has been automated by means of software designed by different companies. Amongst all the techniques finite-difference time-domain (FDTD) technique is most widely used because it provides solution to the Maxwell equations i.e. propagating electromagnetic (EM) fields with respect to time can be directly studied.

Recent developments on photonic crystals show that it will take over other conventional techniques in next couple of decades. A lot of research has been done by many researchers in the field of photonic crystals like: Micro-spectrometer, actuated electromechanically has been demonstrated that provides displacement sensing with resolution of 80pm and rejection ratio 30dB [1], using 3D FDTD technique a photonic crystal based sensor has been designed with sensitivity of refractive index 115.60nm/RIU (Refractive Index Unit) with detection limit of 8.65×10^{-5}[2], bio-chemical sensor based on ring resonator along with slot waveguide has been demonstrated with minimum detection limit of refractive index variation of 2×10^{-4} nm/RIU [3], a biochemical sensor based on photonic crystals with micro-cavity has been designed [4], not only the photonic crystal sensor but photonic crystal based laser sources have also been realized by many researchers: Photonic crystal based laser source has been realized for chemical detection with molecular sensitivity [5], a photonic crystal based gas sensor has been demonstrated, showing dependence of resonant wavelength on refractive index with high quality factor [6] etc.

In recent developments of photonic crystals, apart from technical advancements, use of photonic crystals in bio-sensing is gaining a lot of attention. Traditionally used methods in bio-sensing applications involve labeled sensing in which bio-molecules are labeled with fluorescent/radioactive tags. Labeling of bio-molecules makes diagnosis process complex. Label-free sensing is a popular research area because it reduces complexity with reasonable margin. Techniques that involve label-free sensing are interferometry and use of photonic crystals. Though interferometry does not perform well with biological substances, photonic crystal is a very good alternative because of its superior properties such as higher accuracy, energy efficiency, faster response etc.

II. LATEST RESEARCH ON SENSORS BASED ON PHOTONIC CRYSTALS

Photonic crystals have greater potential to assist medical science for detection and treatment of fatal diseases like tumor and cancer. They are fancied by researchers because of efficient, accurate and fast results. A few papers related to various applications of photonic crystals have been reviewed.

Significant results in cancer detection have been achieved using hybrid defect structure in photonic crystals [7]. Nano-cavity has been coupled with waveguide in photonic crystal to design highly sensitive platform for detection of different cancer cell blood lines. The concept that has been used in this research is: affected (unhealthy) cancerous blood cells in human body differ from healthy blood cells by the amount of protein contained in them. When blood sample is placed in the nano-cavity then index of refraction of the cavity changes for input light and resonant wavelength shift appears with a very good margin and hence cancer for different blood cell lines gets detected.

Photonic crystal based biosensor with four channels [8] has been designed and simulated for respective nano- cavities. 2D FDTD technique has been used for simulations and optimizations for better results. A multichannel biosensor has been designed because generally single channel biosensors are for single sensing purpose only. Biomaterials placed in nano-cavities changed effective refractive index that resulted in high resonant wavelength shift at the output terminal. As per their results, this sensor can be employed for sensing of bio-chemicals e.g. protein, DNA molecules & refractive index.

Photonic crystal with point defect forming cavity [9] has been designed for chemical sensing. Investigation of shifts in cavity resonance because of changes in refractive index of background material has been done and refractive index changes have been observed by modulating the radius of air hole. 3D FDTD method has been used for the analysis of the crystal. Response factor is increased by enhancing the field overlapping with background material using three methods like decreasing thickness of slab, introducing a slot in waveguide and making holes at the centre of waveguide. To increase response factor and improving quality factor, these methods of optimization of cavities are applicable to any photonic crystal hetero-structure cavity formed by modulation of lattice constant, refractive index, air hole radius and the width.

2D Ultra sensitive photonic crystal micro-cavity biosensor [10] has been demonstrated for protein detection. Performance of the device has been verified by calculating the red shifts corresponding to bonding of bovine serum albumin and glutaraldehyde. Optical bio-sensing technique has been used for protein detection because it is a label free detection that it does not require any labeling of fluorescent / radioactive labels which increases complexity and contamination of biological materials. Protein detection is based on surface chemistry and hence instead filling pores and varying ambient refractive index, the molecules coat pore walls.

A biosensor with multiple channels has been designed on photonic crystal waveguide and micro-cavities [11]. Point defect and line defect has been introduced in the photonic crystal to achieve high value of quality factor. Transmission spectra and band structures has been obtained using FDTD technique. Simulation results show that the device has very good sensitivity for refractive index variations provided by introducing analyte in the point defect. For bio-sensing purpose, best defect is point defect in photonic crystal because it provides transmission spectra with narrow transmission peaks. The structure can be optimized further to get separable transmission peaks with good margin for different bio-materials. Bio-sensors that use different techniques like Raman spectroscopy and absorption measurements can be benefitted by the use of photonic crystal bio-sensor with micro-cavity having high quality factor to induce very high optical intensity.

An integrated bio-chip [12] has been designed for live detection of refractive index for single living cell. No fluorescent / radioactive labeling is required since this detection is based on refractive index change of living cell. Various techniques are available to calculate the refractive index of liquid like interferometry that includes Rayleigh refractometer, Michelson and Fabry-Perot interferometer, Mach-Zehnder and many more. In these methods, refractive index is measured by measuring critical angle of total reflection, interference patterns or backscatter. These techniques have their various disadvantages like they are very much prone to noise (process gets influenced by human breath), also, these techniques are performed in huge and expensive machines and trained operators are required to operate them.

An optical sensor has been designed with reasonable quality factor by introducing ring slot structure [13]. Ring slot structure as cavity couples light at input & output by line-defect photonic crystal waveguide. By setting width of 0.20a of ring slot waveguide, quality factor of 10^7 has been achieved using 2D finite different time domain simulation tool. Sensitivity of index of refraction of 160nm/RIU & detection limit of 8.75×10^{-5} has been achieved. This proposed sensor can be used for high quality factor and applicable to detect refractive index to sense the presence of surface molecule.

Pressure sensor using photonic crystals has been designed without any torsion, with improved sensitivity by introducing piston type micro-cavity [14]. To analyze the performances of the designed sensor, the simulation tools used are finite element method (FEM) and finite difference time domain (FDTD). These simulation tools are more attracted by researchers to analyze optical properties of optical sensors relevant to resonant mode for defects and applied strain in pressure sensor. The highest sensitivity of pressure sensor achieved is 0.50nm/nN. Conventional way of sensing pressure are Mach-Zehnder interferometer and optical fibers, however Mach-Zehnder face challenges in forming array of sensor and non-linear output and pressure sensors using fibers are difficult to form using conventional fabrication method. The minimum pressure that can be sensed using sensor is found to be 0.68nN. In comparison with ring resonator based pressure sensor having same sensitivity, size of designed sensor is three orders less in magnitude.

Significant results have been verified using photonic crystal fiber, with gratings having long period for sensing of bio-chemicals [15]. Bio-molecules layer is observed on sides of air holes and shift in resonant wavelength of long period grating has been observed. Thickness of single layer of poly-L-lysine and double stranded DNA has been measured. In form of resonant wavelength, measured sensitivity of long period grating is approximately 1.4nm/1nm, per unit thickness of layer of bio-molecule.

A sensor has been introduced, designed & simulated for the measurement of high temperatures. 2D photonic crystal sensor [16] has been fabricated on silicon wafers by making use of anisotropic etching. Temperature measurements of the sensor are monitored in terms of reflectance spectrum for a range of wavelengths (1250nm to 1650nm). For a temperature range (100^0C to 700^0C), shift in reflectivity peaks has been found to be 0.11 nm/^{0}C. Other methods of temperature measurements are fiber bragg grating (FBG) sensors and long period fiber grating sensors. High sensitivity, compactness and sturdiness provide liberty to these sensors to use in worst conditioned environments.

Directional couplers using photonic crystals with InAlGaAs nano-rods [17] has been designed, optimized and performance has been studied. Photonic crystal directional coupler has been used for the separation of light of two wavelengths (1.31μm and 1.55μm). Structure based on photonic crystals is formed by arrangement of InAlGaAs nano-rods in square latticework. In designed directional coupler, coupling length of the light at 1.31μm is four times greater than at 1.55μm.This logic gives us ability to separate two different wavelengths. The device has been fabricated using electron beam lithography and photolithography. Fabricated device performance in terms of propagation of light has been studied using FDTD simulation tool.

A study of nano-ring resonator using photonic crystals [18] has been demonstrated for bio-chemical sensing applications. Nano-ring resonator has been designed using photonic crystals by missing holes in hexagonal fashion along with two waveguides (for input and output of propagating light). Photonic crystal waveguide is in hexagonal geometry and then two bus waveguides are introduced along with nano-ring resonator cavity defect. This is label free optical sensing that does not include fluorescent / radioactive labeling of bio-molecules. According to the study, resonance peak having reasonable quality factor of 3000 has been reported. Generally two sensing mechanisms are used, one is to measure refractive index change of cavity covered by bio-molecule and second is surface sensing that includes measurement of the bio-molecule layer thickness change at the inner side of the cavity or defect. The quality factor of non-ring resonator for the structure having two holes and three holes coupling distances are found to be 2400 and 3200 respectively. Resonant wavelength is found to be directly proportional to refractive index change and has dependency on location of sensing holes.

A bio-sensor based on photonic crystal has been introduced to detect glucose concentration in urine [19]. Sensor includes L - shaped waveguides along with ring resonator. Glucose found in urine is termed as Glycosuria (0mg/dl to 15mg/dl). If glucose level is higher than mentioned then it indicates high glucose level in blood sample. Glucose level in normal blood sample is 165mg/dl to 180mg/dl. Low glucose level in unhealthy blood sample is termed as Hypoglycemia and higher than normal is termed as Hyperglycemia (ranging from 270md/dl to 360md/dl). Biosensor is proposed to detect glucose level within range 0mg/dl and 15mg/dl. Design parameters that have been used for designing are: configuration is rods in air, shape of rods is circular, latticework structure is cubic/square, lattice constant (a) = 0.540 μm, rod radius is 0.1 μm, rod's refractive index is 3.46, dielectric constant of Si rods = 11.97.

A nano-cavity coupled with 2D photonic crystal waveguide [20] has been demonstrated to detect different blood components. Bio-sensors have numerous applications in medical science, weather monitoring, health care etc. Structure introduced has hexagonal lattice with area of 19×15 μm^2. To study performance analysis, simulation of light propagation has been done using FDTD method. Bio-sensor is claimed to detect blood plasma, cytop, ethanol, water, acetone, tocopherol and sylgard184.

Imaging of detection of cancerous cell's toxicity and proliferation has been introduced using photonic crystal bio-sensor [21]. This is a label free technique i.e. no fluorescent / radioactive labeling is required. Proposed bio- sensor is a 1D photonic crystal that comprises of grating structure with periodicity of 550nm formed using ultraviolet cured polymer with use of room temperature replica molding process on a transparent polyester sheet. Ability of the proposed sensor to capture multiple images of same cells allows not only two step before and after comparison but also allows multi – stepped movies of the behavior of the cell that involves cytotoxicity and proliferation.

Above discussion in literature review provides an overview of how much research has been done by implying photonic crystals in many applications using point defect, line defect or combination of the two. Besides this overview further inferences can be drawn from the work done studied as shown in Table1.

TABLE1. INFERENCES DRAWN FROM LITERATURE REVIEW.

REFERENCES	TECHNIQUE	PARAMETERS	FINDINGS
[7]	• Nano-cavity coupled photonic crystal waveguide.	• Lattice constant= 0.8 μm • Input source= 1550nm • Length of Si rods = 1.5 μm • Air hole radius= 0.3a • SiO2 layer thickness= 3 μm • A named rods shift=0.19 • B named rods shift =0.2 • C named rods shift =0.075 • A- radius = 0.312a.	• Resonant wavelength = 1.797 μm • Sensitivity = 388.57nm/RIU • Quality factor = 4856.75
[8]	• Four-channel photonic crystal with one bus waveguide and four nano-cavities corresponding to each channel.	• Photonic band gap range: (0.22054 to 0.32550) • Refractive index of four nano-cavities: n1 = 1.25 n2 = 1.5 n3 = 1.75 n4 = 2	• Quality factor for: ○ CH1=1976.71 ○ CH2=1999.86 ○ CH3=3549.5 ○ CH4=4793.6 • Transmission efficiency: ○ CH1=76.59% ○ CH2=61.27% ○ CH3=59.53% ○ CH4=62.13%
[9]	• Hetero-structure cavity using air hole modulation. • Using defects: line defect, introducing row of air holes and slot waveguide.	• Input wavelength = 1.55 μm • Width of the waveguide: • S3 = 0.625a • Thinner S3 = 0.225a • T3 with slot waveguide = 0.625a • S3 with center holes = 0.225a • Thinner T3 with slot waveguide = 0.225a	• Quality factor for: ○ S3cavity =7.83×10^6 ○ Thinner S3=1.58×10^6 ○ S3 with center holes=3.82×10^6 ○ T3 with slot waveguide=1.01×10^6 ○ Thinner S3 with center holes=7.30×10^6 ○ Thinner T3 with slot waveguide=1.03×10^6 • Response factor for: ○ S3cavity =0.047 ○ Thinner S3=0.119 ○ S3 with center

			holes=0.110 ○ T3 with slot waveguide=0.232 ○ Thinner S3 with center holes=0.200 ○ Thinner T3 with slot waveguide=0.330 • Sensitivity (at λ=1.55μm) for: ○ S3cavity =73 ○ Thinner S3=184 ○ S3 with center holes=171 ○ T3 with slot waveguide=360 ○ Thinner S3 with center holes=310 ○ Thinner T3 with slot waveguide=512 **Note:** Values of response factor and quality factor corresponds to respective values of sensitivity.
[10]	• Photonic crystal with hexagonal array of cylindrical air pores in 400nm thick Si slab. • Fabrication with silicon on insulator.	• Input wavelength=1440nm to1590nm. • Lattice constant = 465nm. • Pore diameter = 270nm. • Center pore diameter = 140nm.	• Monitoring of binding of bovine serum albumin (BSA) to glutaraldehyde is done by studying resonance red-shift. • Presence of 2.5fg of analyte can be detected at present.
[11]	• Multi-channel photonic crystal with one bus waveguide, four micro-cavities and four drop/output waveguides.	• Dielectric constant = 11.97 • Radius of air holes = 0.4a • Refractive index of cavities: n1 = 2025 n2 = 2 n3 = 1.75 n4 = 1.5	• Properties of the analyte can be determined using designed highly sensitive structure by detecting refractive index of the analyte
[12]	• Interferometry ○ Mach-Zehnder interferometer ○ Michelson interferometer ○ Fabry-Perot interferometer • Integrated Bio-chip technique. • Microscopic imaging ○ Olympus Micro Image 4.5.1 software	Refractive index for five different types of cancerous cells.	Calculated refractive index: 1. Culture medium = 1.350 2. HeLa = 1.392 3. PC12 = 1.395 4. MDA-MB-231 = 1.399 5. MCF-7 = 1.401 6. Jurkat = 1.390 Accuracy with error = 0.25%
[13]	• Photonic crystal waveguide with ring slot structure as point defect with triangular lattice hole array.	• Lattice constant = 378nm • Radius of air holes (r) = 0.34a • Refractive index of Si slab = 3.48 • Width of ring slot (w) = 0.28a • Width of centre hole in ring-slot = 0.34a • Width of waveguide (w1) = $(3a)^{1/2}$	• Quality factor = 11477.3 for width of ring slot = 0.28a • Sensitivity = 160nm/RIU • Minimum Detection limit = 8.75×10^{-5} RIU

[14]	• Photonic crystal waveguide with piston type micro-cavity with air holes in Si slab in triangular lattice fashion.	• Refractive index of Si slab (n)=346 • Radius of air holes = 0.32a • Lattice constant = 425nm • Crystal slab thickness = 0.56a • Thickness of piston-rod = 226nm • Distance between piston rod and air hole (d) = 3a • Radius of centre air hole = 0.17a	• Sensitivity = 0.50nm/nN • Minimum detectable pressure = 0.68nN
[15]	Photonic crystal fiber with gratings having long period (PCF-LPG)	• Lattice constant = 7.2 μm • Number of period grating = 26 • Grating length = 18.2mm • Fiber length with PCF-LPG grating is = 30cm	• PCF-LPG resonant wavelength shift for: ○ Poly-L-lysine layer = 6.7nm ○ Monolayer of double-stranded DNA = 2.3nm • Average thickness of poly-L-lysine layer = 4.79nm • Average thickness of DNA monolayer = 1.64nm
[16]	• Attaching photonic crystal to the smooth surface of the single mode fiber. • Bonding of photonic element with Si welding. • GOPHER process.	• Input wavelength = 1250nm to 1650nm • Square lattice with circular holes with hole diameter = 700nm	• Monitoring the temperature of Si photonic crystal waveguide has been done by measuring reflectance spectrum for 1250nm to 1650nm wavelength range. • Reflectivity peak shift or sensitivity is 0.11nm/^{0}C for temperature range 100^{0}C to 700^{0}C.
[17]	• <u>Fabrication techniques:</u> ○ e – beam lithography ○ Photolithography	• Coupling length • Width of slab waveguide = 5 μm	• Designed structure is able to separate two wavelengths 1.31μm and 1.55μm and propagate them in drop waveguides by following the logic that coupling length for 1.31μm wavelength must be four times higher than the coupling length for 1.55μm wavelength.
[18]	• Photonic crystal with nano-ring as point defect with one input and one output waveguide.	• SiO_2 slab thickness = 220nm • Lattice constant = 410nm • Radius of air holes = 120nm • Coupling distance	• For two and three hole coupling distance, the values of derived quality factor are 2400 and 3200 respectively. • For two and three hole coupling distances the values of minimum detectable weight of bio-molecule are 0.23fg and 0.2fg respectively.
[19]	• Photonic crystal with two inverted-L shape waveguides as input and output waveguides with a ring resonator as defect at the centre of the crystal structure.	• Operating wavelength range = 1540nm to 1550nm. • Dimensions of bio-sensor are 11.4μm × 11.4μm. • Lattice constant/Period of Si Rods = 0.540 μm • Radius of Si rods = 0.1μm • Index of refraction for Si rods = 3.46 • Dielectric constant of Si rods = 11.97	• Obtained optimized results in the form of glucose concentration, albumin concentration, urea concentration and bilirubin concentration in urine in terms of index of refraction, resonance wavelength, normalized output power & quality factor.

[20]	• Coupling of nano-cavity with photonic crystal waveguide in hexagonal array arrangement of Si rods.	• Area if hexagonal array = 19×15 μm^2 • Lattice constant/Period of Si rods = 690nm • Index of refraction of Si rods = 3.6730 • Radius of Si rods = 220nm • Operating range = 1500nm to 1700nm.	• Designed sensor can sense bio-materials like ethanol, acetone, blood plasma, water, tocopherol, cytop and sylgard184. • Optimized transmission peak and refractive index values for various blood components (cytop, blood plasma, tocopherol, acetone,ethanol, sylgard184, water) has been achieved.
[21]	• Label – Free detection • Imaging spectrometry	• Peak Wavelength Value (PWV) • Periodic grating structure with period = 550nm	• Incubation of MCF-7 cancer cell line proliferation has been achieved with increase of 200% for Sapindus mukurossi & 283% for Protium serratum. • Peak wavelength value imaging is achieved. • Ability of the proposed sensor to capture multiple images of same cells allows not only two steps before and after comparing but also allows multi–steps movies of the behavior of the cell that involves cytotoxicity and proliferation.

III. CONCLUSION

It has been observed that photonics is one of the most fancied research fields to work on because of its numerous advantages over conventional methods for performing and monitoring applications. Key points that prove photonics to be an emerging technology in today's world are their better accuracy, efficiency, fast response, low cost and simple handling. It has been observed that photonic devices with optical fibers have their limitations in miniaturization of devices. At this stage photonic crystals come into picture that gives us liberty of localizing the different modes of light from photonic band gap frequencies and also miniaturizing devices that gives us the idea of nano-photonic crystals. According to current research in photonic crystals, it has been observed that photonic crystals can be used in wide variety of applications like in weather monitoring, detection and treatment of many diseases like cancer, drug analysis in pharmaceuticals etc.

Hence study shows that photonic crystals have very good scope in many live applications that make things better and simpler because of different viewing angle of understanding technology related to propagation of light which further may provide a good future to humanity ahead.

REFERENCES

[1] Z. Zobenica *et al.*, "Integrated spectrometer and displacement sensor based on mechanically tunable photonic crystals," *Int. Conf. Opt. MEMS Nanophotonics*, pp. 1–2, 2017.

[2] D. Yang, H. Tian, and Y. Ji, "Nanoscale photonic crystal sensor arrays on monolithic substrates using side-coupled resonant cavity arrays," *Opt. Express*, vol. 19, no. 21, p. 20023, 2011.

[3] C. A. Barrios *et al.*, "Bar07-Ol," vol. 32, no. 21, pp. 3080–3082, 2007.

[4] E. Chow, A. Grot, L. W. Mirkarimi, M. Sigalas, and G. Girolami, "Cho04-Ol," vol. 29, no. 10, pp. 1093–1095, 2004.

[5] M. Lončar, A. Scherer, and Y. Qiu, "Photonic crystal laser sources for chemical detection," *Appl. Phys. Lett.*, vol. 82, no. 26, pp. 4648–4650, 2003.

[6] A. Forchel *et al.*, "Photonic crystal cavity based gas sensor," *Appl. Phys. Lett.*, vol. 92, no. 26, p. 261112, 2008.

[7] S. Jindal, S. Sobti, M. Kumar, S. Sharma, and M. K. Pal, "Nanocavity-Coupled Photonic Crystal Waveguide as," *IEEE Sens. J.*, vol. 16, no. 10, pp. 3705–3710, 2016.

[8] S. Olyaee, S. Najafgholinezhad, and H. Alipour Banaei, "Four-channel label-free photonic crystal biosensor using nanocavity resonators," *Photonic Sensors*, vol. 3, no. 3, pp. 231–236, 2013.

[9] S.-H. Kwon, T. Sünner, M. Kamp, and A. Forchel, "Optimization of photonic crystal cavity for chemical sensing," *Opt. Express*, vol. 16, no. 16, p. 11709, 2008.

[10] M. R. Lee and P. M. Fauchet, "Two-dimensional silicon photonic crystal based biosensing platform for protein detection," *Opt. Express*, vol. 15, no. 8, p. 4530, 2007.

[11] M. Yun, Y. Wan, J. Liang, F. Xia, M. Liu, and L. Ren, "Multi-channel biosensor based on photonic crystal waveguide and microcavities," *Optik (Stuttg).*, vol. 123, no. 21, pp. 1920–1922, 2012.

[12] X. J. Liang *et al.*, "Determination of Refractive Index for Single," pp. 1712–1715, 2005.

[13] L. Huang, H. Tian, J. Zhou, Q. Liu, P. Zhang, and Y. Ji, "Label-free optical sensor by designing a high-Q photonic crystal ring-slot structure," *Opt. Commun.*, vol. 335, pp. 73–77, 2015.

[14] D. Yang, H. Tian, N. Wu, Y. Yang, and Y. Ji, "Nanoscale torsion-free photonic crystal pressure sensor with ultra-high sensitivity based on side-coupled piston-type microcavity," *Sensors Actuators, A Phys.*, vol. 199, pp. 30–36, 2013.

[15] L. Rindorf, J. B. Jensen, M. Dufva, L. H. Pedersen, P. E. Høiby, and O. Bang, "Photonic crystal fiber long-period gratings for biochemical sensing.," *Opt. Express*, vol. 14, no. 18, pp. 8224–31, 2006.

[16] B. Park, J. Provine, I. W. Jung, R. T. Howe, and O. Solgaard, "Photonic Crystal Fiber Tip Sensor for High-Temperature Measurement," *Sensors (Peterborough, NH)*, vol. 11, no. 11, pp. 2643–2648, 2011.

[17] C.-C. Chen *et al.*, "Photonic crystal directional couplers formed by InAlGaAs nano-rods," *Opt. Express*, vol. 13, no. 1, p. 38, 2005.

[18] F. L. Hsiao and C. Lee, "Computational study of photonic crystals nano-ring resonator for biochemical sensing," *IEEE Sens. J.*, vol. 10, no. 7, pp. 1185–1191, 2010.

[19] S. Robinson and N. Dhanlaksmi, "Photonic crystal based biosensor for the detection of glucose concentration in urine," *Photonic Sensors*, vol. 7, no. 1, pp. 11–19, 2017.

[20] S. Ameta, A. Sharma, and P. K. Inaniya, "Nanocavity coupled waveguide photonic crystal biosensor for detection of different blood components," *Proceeding - IEEE Int. Conf. Comput. Commun. Autom. ICCCA 2017*, vol. 2017–January, pp. 1554–1557, 2017.

[21] L. L. Chan, S. L. Gosangari, K. L. Watkin, and B. T. Cunningham, "A label-free photonic crystal biosensor imaging method for detection of cancer cell cytotoxicity and proliferation," *Apoptosis*, vol. 12, no. 6, pp. 1061–1068, 2007.