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Two-curve-shaped biosensor using photonic crystal nano-ring resonators

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Abstract

We design a novel nano-ring resonator using two-dimensional photonic crystal (2D-PhC), for bio-sensing applications. The structure of biosensor is created by two-curve-shaped ring resonator which sandwiched by two waveguides. These are configured by removing one row of air holes. The refractive index of sensing hole is changed by binding an analyte. Hence, intensity of the transmission spectrum shifts to lower value. This process is utilized for determining the properties of the analyte. The quality factor is obtained about 1550 and for a unit change in the refractive index of sensing hole, the intensity of transmission spectrum reduces as 4.125 units.

1. Introduction

Photonic Crystals (PhCs) are the periodic structures that can control and guide the photons in the periodic lattice [1]. This periodicity results in a wavelength region in which propagation of optical waves is prohibited. This wavelength region is called the photonic band gap (PBG). Due to the PBG's properties, these structures are capable of confining and controlling the light inside small spaces that is the key for realizing all optical integrated circuits [2].

The photonic crystals are presented for various applications such as photonic crystal fibers, photonic crystal multiplexers and de-multiplexers, photonic crystal filters, photonic crystal sensors, etc. The photonic crystals are as an attractive sensing platform due to the control light in very small dimensions, fabricated with standard CMOS techniques, and easy integration to photonic integrated circuits [3-10]. Also, these can be designed to localize the electric field in the low refractive index region and make the sensors extremely sensitive to a small refractive index change.

In recent years, various sensors based on photonic crystal are presented. Yang *et al*. have reported a micro-displacement sensor [3]. This sensor formed by a fixed and a mobile photonic crystal segment. Olyaee*et al*. have proposed a novel small size fourchannel biosensor based on nano-cavities [4]. The nano-scale optical biosensors are used for fast and reliable analytical appliances which require to the monitoring and regulating different parameters in areas such as nano-technology, biomedical research, etc. [5]. Other applications of photonic crystal sensors such as gas sensors [6], pressure sensors [7], and refractive index detectors [8] have been also reported.

So far, various structures of photonic crystals submit for bio-sensing applications. These structures are such as photonic crystal waveguides, photonic crystal fibers, photonic crystal micro- and nano-cavities, and photonic crystal ring resonators. The present research is focused on photonic crystal ring resonator-based biosensors.

The ring resonator is made by a ring waveguide which sandwiched by two straight waveguides. At first, Kim *et al*. was proposed and demonstrated photonic crystal ring resonator (PCRR) for a hexagonal ring laser [9]. This structure consisted of six waveguides and the ring diameter of this PCRR was about 7.5 µm. Then Kumar *et al*. investigated the ring resonators in photonic crystal circuits [10]. They demonstrated that the waveguide-coupled ring in a photonic crystal behaves like resonator when the effect of waveguide coupling between the waveguide and the ring arm was reduced.

The PCRR are designed by various shapes such as square and quasi-square-shape PCRR [11], X-shape PCRR [12], T-shape PCRR [13], L-shape PCRR [14], hexagonal-shape PCRR [15], and diamond-shape PCRR [16]. PCRRs are common structures for designing optical filters and most of top structures have been proposed for optical channel-drop or add-drop filters [11-14]. PCRRs can also be used for realizing optical sensors, optical switches, optical de-multiplexers, etc.

Recently, various sensors based on photonic crystal ring resonators are presented. Hsiao and Lee investigated and optimized a PCRR for biochemical sensing [15]. The ring resonator formed by removing air holes of a hexagon from. The size of hexagonal ring radius was about five-holes and the quality factor was 3200. The sensitivity was equal to 0.5 nm/fg. By putting together two hexagonal ring resonators, biosensor based dual nano ring resonator (DNRR) has been reported [17]. The quality factor of this sensor was lower than quality factor of biosensor based single nano ring resonator (SNRR). The SNRR biosensor showed a better resonance wavelength shifts and lower stability with comparison of DNRR.

Li and Lee proposed a nano-scale force sensor based PCRR [18]. The resonator was formed by triple nano-ring resonator (TNRR). The size of each hexagonal ring was 2.87 µm. The quality factor and the minimum detectable force of sensor were 1412 and 0.847 µN, respectively. Also, Ho *et al*. reported the design of a TNRR with the ability to be implemented in bio-sensing [19].

Recently, a diamond-shaped biosensor has been reported [16] whichin the structure,a ring resonator and two waveguides are formed by reduction of radius of air holes. The size of the diameter of nano-ring resonator is 1.1 µm. Then sensor characteristics are investigated and the performance of the diamond-shaped nano-ring resonator is optimized. The quality factor and the sensitivity are 3700 and 3.4 nm/fg, respectively.

In this paper, we propose a nano-ring resonator biosensor based on the two-dimensional photonic crystal. The structure of biosensor are shaped by two mixed curvatures ring resonator which sandwiched by two waveguides. For choosing the best hole for binding the analyte, six holes of surrounding holes of the ring resonator as the sensing element are applied. Then, by comparing the results of intensity variation, we choose one of them as the sensing element. This research focuses on the designing of a high sensitivity biosensor. A comparison of the properties of the present biosensor with some designs presented in literature survey reveals the novelty of present biosensor. The high quality factor, high sensitivity, and reasonably regression coefficient are some major characteristics which are important in biosensing applications.

2. Sensing mechanism

The bio-sensing mechanism is based on the effective refractive index change of the sensing hole. By binding an analyte into the sensing hole, one of the features of the transmission spectrum will be changed. This process was utilized for determining the properties of the analyte. There are two types of sensing mechanism which the sensor can be calibrated; the resonant wavelength shift (RWS) scheme and the intensity variation (IV) scheme [20].

In RWS scheme, the amount of change in resonant wavelength is measured to detect presence of analytes. This scheme is used to measure a wider range that is determined by the free spectral range. Narrow full width at half maximum (FWHM) will improve the precision of RWS based sensors. However, the disadvantage is that the tiny shift in n_{eff} often cannot be determined and highly sensitive electronics are required. The sensitivity can be defined as resonant wavelength shift per refractive index unit (RIU).

In IV scheme, the amount of intensity change at the resonant frequency at the output is measured to detect the presence of analytes. Compared to the RWS scheme, the IV scheme requires simple apparatus. The disadvantage is that only a narrow range of wavelength shift can be measured. A broader FWHM will be desirable in this case because at smaller slope values a finer calibration can be achieved. The IV scheme sensitivity is defined as intensity shift per RIU.

3. Designing photonic crystal biosensor

Schematic of the biosensor based on photonic crystal nano-ring resonator using 2D-PhC is shown in Figure 1. In our design, the hexagonal lattice of air holes in dielectric slap with the lattice constant equal to 410 nm and radius of air holes equal to 120 nm is used. The effective refractive index of air and silicon are respectively considered as 1 and 2.825. Defects into the structure are configured by removing one row of air holes.

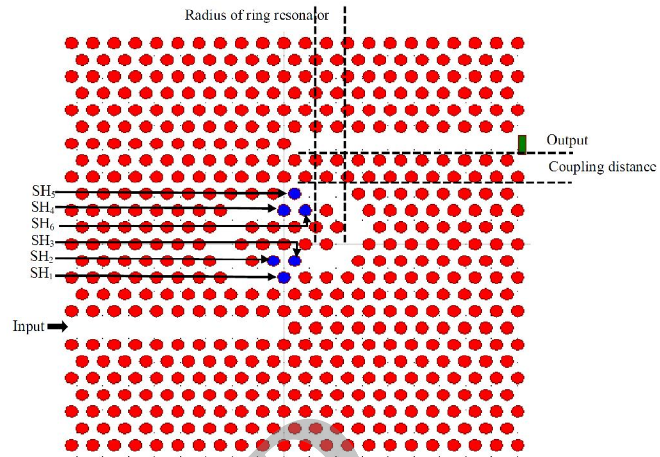

Fig.1. Sketchof the bio-sensor based on photonic crystal nano-ring resonator. Beneath the waveguide is the input and top of the waveguide is the output. The coupling distance, sensing holes, and the radius of ring resonator are marked on figure.

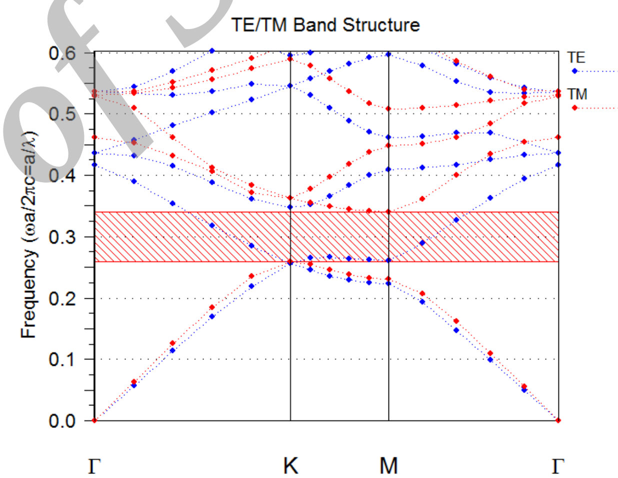

Fig.2. Band structure of the photonic crystal structure.

The defects consist of a ring resonator and two waveguides. The ring resonator is formed by two mixed curvatures and sandwiched by two waveguides. The lower and upper waveguides are respectively considered as the input and output. The coupling distance between ring resonator and waveguides are two rows of air holes. The sensing holes, the coupling distance, and the ring radius are denoted on Figure 1.

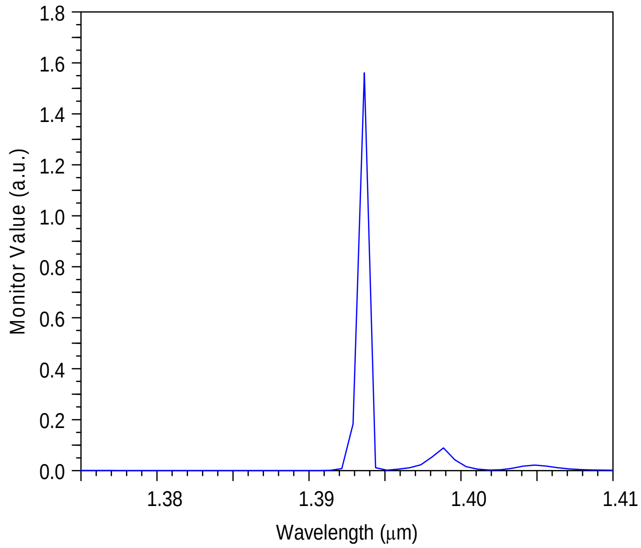

Fig.3. The output transmission spectra of the nano-ring resonator. The resonant peak wavelength gets at 1393.6 nm and the quality factor reveals about 1700.

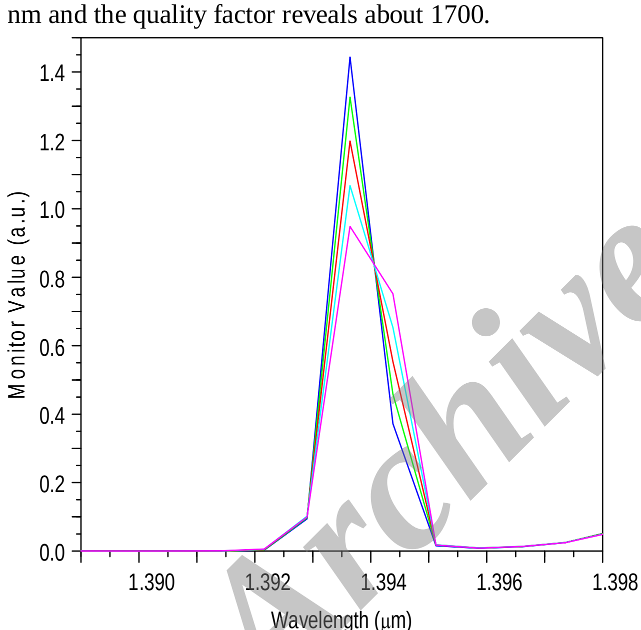

Fig.4. The resonant wavelength of various refractive indexes in SH_1. By increasing the refractive index in sensing hole, the intensity of the transmission spectrum is shifted to lower values.

By plane wave expansion method, the photonic band gap (PBG) of structure is calculated. The band diagram of the photonic crystal structure is displayed in Figure 2. This hexagonal lattice does not exhibit band gap for TE gap. For TM gap the PBG is between 0.258 and 0.340. The corresponding wavelength ranges from 1205 to 1640 nm.

4. Simulation results

A temporal pulse source and a time monitor are fixed at the input and output waveguides. By coupling the light source to the input waveguide, the resonant mode of the ring resonator is excited and the resonant light coupled to the output waveguide. The transmission spectra at the output waveguide are recorded by a time monitor. The output spectrum of the ring resonator is shown in Figure 3. In this case, the resonant peak wavelength gets at 1393.6 nm. The quality factor, the ratio of the resonating wavelength and the FWHM, reveals about 1700 at the resonant wavelength.

In this paper, the sensing mechanism is based on IV scheme. To select the best sensing hole, six holes of the ring resonator are applied and conditions for higher sensitivity is investigated. The six sensing holes (SH) are pointed in Figure 1.Therefore, the transmission spectra are gotten at two state of different refractive index of sensing hole. First, the refractive index of sensing hole is varied from 1 to 1.33 (the refractive index of sensing hole containing water) and then it is varied from 1 to 1.45 (the refractive index at bindingDNA molecules to the sensing hole). The respective quality factor, intensity of transmission spectra, and sensitivity are listed in Table 1. Comparing the results of the various states of the sensing hole realizes that the SH_1 has higher sensitivity. Also, if higher quality factor and higher sensitivity simultaneously are important, the SH_5 is the best sensing hole. The quality factor for SH_1 and SH_5 are about 1550 and 1740, respectively. For a unit change in the refractive index of SH_1 and SH_5, intensities of transmission spectrum reduce as 4.125 and 3.741 units, respectively. As a result, SH_1 has the better sensitivity. As previously mentioned, the sensitivity of the present biosensor isdefined as resonant wavelength shift per refractive index unit which can be positive or negative as listed in Table 1, depending on the selected sensing hole.

Table.1. The list of quality factor, intensity of transmission spectra, and sensitivity for different sensing holes.

Sensing hole	Quality factor	Intensity of transmission spectraat n=1.33	Intensity of transmission spectraat n=1.45	Sensitivity
SH_1	1550	1.445	0.950	4.125
SH_2	1740	1.384	1.125	2.158
SH_3	1765	1.970	2.070	-0.830
SH_4	1750	1.810	1.823	-0.185
SH_5	1740	1.439	0.990	3.741
SH_6	1740	1.638	1.405	1.941

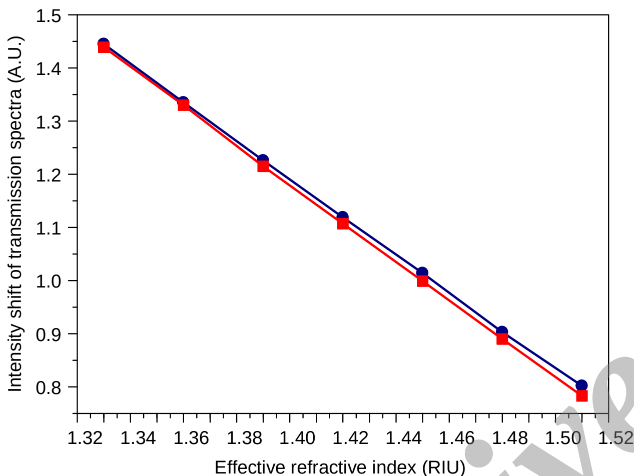

Fig.5. Normalized curve of the intensity of resonant wavelength with respect to the effective refractive index in sensing hole. Curves marked by closed circle and closed square represent normalized curves of SH_1 and SH_5, respectively.

The effective refractive index of SH_1 and SH_5 is changed in the range of 1.33 to 1.51. The results of SH_1 and SH_5 are similar to another, but the transmission spectrum of SH_5 has higher quality factor and lower intensity shift. The resonant wavelength of various refractive indexes in SH_1 is shown in Figure 4. By increasing the refractive index of the sensing hole, the intensity of the transmission spectrum is shifted to lower values. The normalized curves of the intensity shifting are shown in Figure 5. Curves marked by closed circle and closed square represent normalized curves of SH_1 and SH_5, respectively. These curves show approximately linear relationship between refractive index and intensity shift. The regression coefficients of SH_1 and SH_5 are 0.9375 and 0.9998 which shows good linearity relation.

5. Conclusions

We have designed a small size biosensor using the nano-ring resonator. The bio-sensing mechanism has been based on the effective refractive index change of the sensing hole. By binding an analyte into the sensing hole, the intensity of the transmission spectrum has been shifted to lower value. By comparison of the results of the various states of the sensing hole, SH_1 and SH_5 have been selected. The simulation results showed that the SH_1 has higher sensitivity and the SH_5 has higher quality factor.A comparison of the properties of the present biosensor with some designs presented in literature survey revealed the novelty of present biosensor such as high quality factor, high sensitivity, and reasonably regression coefficient.

References

[1] J.D. Joannopoulos, S.G. Johnson, J.N. Winn, R.D. Meade, Photonic Crystals Molding the Flow of Light, Princeton University Press, New Jersey, USA, 2007.

[2] F. Mehdizadeh, H. Alipour-Banaei, S. Serajmohammadi, Journal of Optics 15 (2013) 1-7.

[3] D. Yang, H. Tian, Y. Ji, Optical Engineering50 (2011) 21-26.

[4] S. Olyaee, S. Najafgholinezhad, H.Alipour-Banaei, Photonic Sensors 3 (2013) 231-236.

[5] S. Ghoshal, D. Mitra, S. Roy, Sensors and Transducers Journal113 (2010) 1-17.

[6] S. Olyaee, A. Naraghi, Photonic Sensors3 (2013) 131-136.

[7] S. Olyaee, A. A. Dehghani, Sensor Letters 11 (2013) 1854-1859.

[8] Y. Li, Z. Liu, S. Jian, Photonic Sensors4 (2014) 21–27.

[9] S.H. Kim, H.Y. Ryu, H.G. Park, G.H. Kim, Y.S. Choi, Y.H. Lee, Applied Physics Letters 81 (2002) 2499-2501.

[10] V.D. Kumar, T. Srinivas, A. Selvarajan, Photonics and Nanostructures 2 (2004) 199-206.

[11] Z. Qiang, W. Zhou, Optics Express 15 (2007) 1823-1831.

[12] M.Y. Mahmoud, G. Bassou, A. Taalbi, Z.M. Chekroun, Optics Communications 285 (2012) 368–372.

[13] M. Djavid, A. Ghaffari, F. Monifi, M.S. Abrishamian, Physica E 40 (2008) 3151– 3154.

[14] M. Djavid, F. Moni, A. Ghaffari, M. S. Abrishamian, PIERS Proceedings, Hangzhou, China, (2008) 1097-1099.

[15] F.L. Hsiao, C. Lee, IEEE Sensors Journal 10 (2010) 1185–1191.

[16] S. Olyaee, A. MohebzadehBahabady, IEEE, IET 10th International Symposium on Communication Systems, Networks and Digital Signal Processing 14 (2014) 23-25.

[17] F.L. Hsiao, C. Lee, J Micro / Nano-lithograph MEMS MOEMS 10 (2011) 013001–013008.

[18] B. Li, C. Lee, Procedia Engineering 5 (2010) 1418–1421.

[19] C.P. Ho, B. Li, A.J. Danner, C. Lee, Microsystems Technology 19 (2012) 53-60.

[20] C. Y. Chao, L. J. Guo, Journal of Lightwave Technology 24 (2006) 1395-1402.