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Design and optimization of diamond-shaped biosensor using photonic crystal nano-ring resonator

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ABSTRACT

In this paper, we present a diamond-shaped biosensor based on the nano-ring resonator using two-dimensional photonic crystal (2D-PhC). The biosensor is consisted of a ring resonator and two waveguides. The ring resonator with two end waveguides on both sides, are placed in the middle of structure. Due to the analyte binding to the sensing hole, the refractive index of hole is changed and consequently the resonant wavelength is shifted. According to the results, the resonant wavelength shift in the range of 1.33–1.54 is linearly proportional to the refractive index variations. The quality factor and the sensitivity of biosensor are respectively obtained about 3700 and 3.4 nm/fg. The minimum detectable biomolecule weight in a sensing hole for a diamond-shaped nano-ring resonator is derived as 0.029 fg.

1. Introduction

In the past decade, fast and reliable analytical devices are required for monitoring and regulating different parameters in areas such as food storage, biomedical research, and production and testing of drugs. The optical biosensors are widely used for these purposes [1–3]. Detection protocols that can be implemented in optical biosensing are categorized into two classes; fluorescence-based and label-free detection. In label-free detection, target molecules are not altered and are detected in their natural forms. This type of detection is relatively easy and cheap to perform. Also some of the label-free detections use refractive index (RI) change mechanism. RI change mechanism is related to the surface density, instead of total sample mass. This characteristic is very important, especially when nano-measurement is involved [3].

The label-free detection is possible to variety of methods such as surface Plasmon resonance, interferometry, optical waveguide, optical fiber, optical ring resonator, and photonic crystal biosensors [3]. The photonic crystals due to the strong light confinement, ability to integrate to the CMOS photonic ICs, structured design with air defects, and accessed to sensors with very sensitive to small changes in the RI, are excellent and attractive sensing platforms [3–12]. The photonic crystal sensors are designed for various applications such as pressure sensors [4,5], displacement measurement systems [6], mechanical sensors [7], refractive index detectors [8], gas sensors [9,10], biosensing systems [11,12], and so on.

In recent years, various structures of photonic crystals have been submitted for biosensing applications that most of them are based on the photonic crystal resonators. Chow et al. designed a biochemical sensor based two-dimensional photonic crystal micro-cavity with quality factor of about 400 [13]. Lee and Fauchet proposed a photonic crystal sensor for protein detection [14,15]. Their structure was based on the photonic crystal micro-cavity. Quan et al. investigated a sensor using photonic crystal nano-beam cavities for glucose detection with concentration of 10 mg/dL [16].

Compared to the other types of resonators, ring resonators display a higher sensitivity and quality factor, especially when their radius is small [17]. The ring resonators apply a ring waveguide sandwiched by two straight waveguides, i.e., bus and drop waveguides. The first report of a photonic crystal ring resonator (PCRR) was in basis of a hexagonal waveguide ring laser cavity [18]. The PCRR laser structure consists of six waveguides and six 120° bends, and the ring diameter has 13 air holes along (about 7.5 μm). Then Kumar et al. investigated the spectral characteristics of the waveguide-coupled rectangular ring resonators in photonic crystals [19].

Qiang et al. studied add-drop filters based on square-lattice PhCs [20]. The quality factor of single square ring filter is enhanced from 160 to over 1000 by increasing the coupling sections between waveguide and ring. By manipulating the refractive index and radius of some scatters in PhCs, they achieved a high transmission,

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three wavelengths channel-drop filter in double ring configuration.

The PCRR based structures that have been reported so far are: (1) Square and quasi-square-shape PCRR, (2) Dual curved-shape PCRR, (3) L-shape PCRR, (4) 45-deg-square shape PCRR, (5) T-shape PCRR, (6) X-shape PCRR, (7) Hexagonal-shape PCRR, and (8) Diamond-shape PCRR [21–27]. Most of these structures have been proposed for optical channel-drop or add-drop filters. The PhCs based ring resonators provide very well optical confinement which can be also used for architecture of photonic crystals sensors [28–34].

Hsiao and Lee investigated a single hexagonal PCRR for biochemical sensing applications [17]. The size of hexagonal ring resonator is as small as 3 μm. They optimized the sensor and showed that the higher coupling distance enhances the quality factor and drop efficiency. The quality factor of the biosensor has been improved to 3200. The sensitivity for the detection of DNA and proteins with a minimum weight of 0.2 fg was equal to 0.5 nm/fg [28,29]. In 2011, the biosensors based on dual nano-ring resonators (DNRR) have been demonstrated and compared to the single nano-ring resonator (SNRR) [30,31]. The quality factor of a SNRR with two-holes coupling distance was 2400 and quality factors for the forward and backward drop of a DNRR were 2100 and 1855, respectively. The wavelength shift of a SNRR is larger than that of DNRR, but the stability of DNRR is better. Li and Lee proposed a hexagonal photonic crystal lattice with triple nano-ring resonator (TNRR), with size of 2.87 μm for each ring, as a nano-scale force sensor [32]. This device gives minimum detectable force of 0.847 μN in the region of applied force from 15 to 20 μN. Also, Ho et al. reported the design of a TNRR to be used as a biosensor [33].

Recently, we have designed a small size biosensor based on diamond-shaped nano-ring resonator [34]. The size of the diameter of nano-ring resonator was as small as 1.1 μm. The quality factor of the proposed structure was about 2840 and the sensitivity for the detection of DNA in sensing hole has been obtained as 3.0 nm/fg.

In this paper, several parameters of the diamond-shaped nano-ring resonator are investigated and the optimized parameters of the PCRR are obtained. The biosensing mechanism is based on the effective refractive index (ERI) change of the sensing hole. By binding an analyte into the sensing hole, the transmission spectrum shifts to longer wavelengths, and this process is utilized for determining the properties of the analyte. This research focuses on the designing of a biosensor with higher optimized sensitivity and quality factor.

2. Design of photonic crystal biosensor

The structure of photonic crystal includes hexagonal lattice of air holes in dielectric. Preliminary sketch of the biosensor based on the photonic crystal nano-ring resonator is shown in Fig. 1. The refractive index of air and silicon are considered as 1 and 2.825, respectively. The lattice constant of the PhC structures and radius of air holes (R_a) are respectively equal to 410 nm and 120 nm. The defects into the structure consist of a ring resonator and two waveguides. The ring resonator is designed as diamond-shape placed in the middle of the structure. The size of diamond nano-ring resonator diameter is equal to three rows of holes, i.e. as small as 1.1 μm. The ring resonator is sandwiched by two waveguides. The bottom waveguide and top waveguide are as input and output waveguides, respectively.

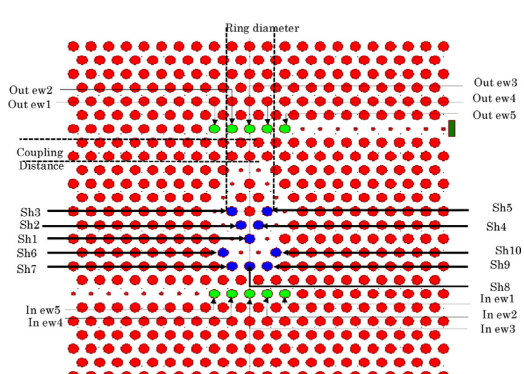

Fig. 1. Sketch of the biosensor based on photonic crystal nano-ring resonator. Beneath the waveguide is the input and top of the waveguide is the output. The sensing holes, the coupling distance, and the ring diameter are marked on figure.

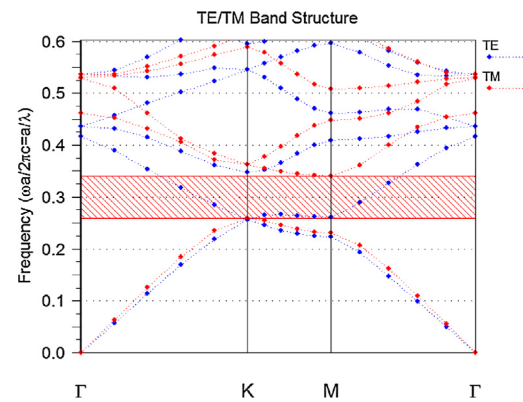

Fig. 2. Band structure of the photonic crystal structure.

The photonic band gap (PBG) of structure is calculated by the plane wave expansion (PWE) method. The band diagram of the PhC structure is demonstrated in Fig. 2. This hexagonal lattice do not exhibits band gap for TE gap and the PBG for TM gap extends from 0.258 to 0.340. The corresponding wavelength ranges from 1205 to 1640 nm.

3. Investigation of sensor characteristics

Several parameters are important to optimize the performance of the diamond-shaped nano-ring resonator such as (1) the coupling distances between the ring resonator and the waveguides, (2) the holes size of the ring resonator and waveguides, (3) the end-holes of the bus and drop waveguides, and (4) selecting the best sensing hole for binding an analyte. The resonant wavelength and output spectra are changed by these parameters.

In integration of PhC waveguides and ring resonator, the coupling distance between the waveguides and resonator is important to improve transmission efficiency. By increasing the coupling distance between the waveguide and the ring resonator, the quality factor is increased, but the ratio of resonance wavelength shift per refractive index change is decreased. This decrease is due to low analyte interaction with light. It also reduces the sensitivity and the intensity of transmission spectra. On the other hand, by reducing the coupling distance, the interaction of light and material can be accelerated in the sensing hole, and this causes to increase the sensitivity and the intensity of transmission spectra. Instead, the quality factor is low. Hence, by selecting two rows of air holes as the coupling distance between the waveguide and ring resonator, all three features of biosensor including the sensitivity, the quality factor, and the intensity of transmission spectra can be simultaneously optimized [12,28].

The ring resonator and two waveguides are formed by reduction of radius of air holes. To choose the best size of the holes of the waveguide (R_w), the structure is simulated considering R_w/R_a ratio in the range of zero to 0.7. The quality factor and the intensity of transmission spectra are measured. According to the results, it was found that in ratio about 0.3, the best parameters are obtained [34]. Here, we have changed the size of the R_w/R_a ratio from 0.26 to 0.39