Photonics and Nanostructures - Fundamentals and Applications 31 (2018) 89–98

Contents lists available at ScienceDirect

Photonics and Nanostructures - Fundamentals and Applications

journal homepage: www.elsevier.com/locate/photonics

Design of a label-free photonic crystal refractive index sensor for biomedical applications

Mohammad Danaie*, Behnam Kiani

Faculty of Electrical and Computer Engineering, Semnan University, Semnan, Iran

ARTICLE INFO

Keywords:
Photonic crystals
Biosensor
Refractive index sensor
Resonators
Optical sensor

ABSTRACT

Two photonic crystal optical refractive index sensors have been proposed in this paper. These sensors can be used for detection of basal cell cancer. A rod-type square lattice of GaAs is used for this purpose. The sensor topologies are based on a photonic crystal ring-shaped resonator coupled to two and waveguides respectively. Instead of using ultra-high quality factor cavities for improving the sensitivity, the resonance profile is localized and concentrated on the analyte to achieve good distinction. A 13 nm cavity resonance frequency shift for normal and cancer cells is obtained for detection of basal cell carcinoma. Finite difference time domain method and plane wave expansion methods are used to simulate and analyze the structures. The proposed biosensors have a sensitivity equal to 720 and 638 nm/RIU. The simplicity of the design and its high sensitivity make it a suitable choice for bio-sensing applications.

1. Introduction

Photonic crystals (PhCs) are composed of periodic lattices of dielectric materials. The periodicity gives them unique optical features. Creation of an optical bandgap is one of their most important specifications [1]. Due to a having a photonic bandgap, PhCs can easily confine light. They have been used to design various types of optical devices such as waveguide components [2–5], optical modulators [6,7], oscillators [8], switches [9–11] etc. PhCs are also among the many frameworks that can be used for design of biosensors. It is mainly due to the fact that very high quality factor (Q-factor) resonators have been implemented and reported in the literature using PhCs [12–14]. The existence of a high Q-factor resonators is the first step for design of many biosensors [15]. PhCs can be easily implemented using integrated circuit (IC) technology on semiconductor substrates. It enables the designer to integrate photonic crystal devices with electrical components on a single chip. If all the elements needed for implementing a biosensor can be integrated on a single chip, obtaining low-cost small-size disposable detection kits can be expected.

Different PhC topologies have been proposed in the literature for realization of biosensors. A PhC optical waveguide is used in [16] as a biosensor. A rod type PhC for which the background dielectric constant changes with respect to the taken sample is used in [16]. The waveguide transmission spectrum changes for different blood components. However, analyzing and interpreting its results are not an easy task. Such a method does not have high sensitivity either. A more sensitive method is to use grating or PhC surfaces as optical reflectors. Such structures, when illuminated with white light, only reflect a single wavelength [17]. When molecules are attached to the surface the reflection spectrum changes. Imaging techniques are then used to record the data for future interpretation [18]. Experimental results using such methods have produced reliable outcomes [19,20]. When 2D PhCs are used as the reflector surfaces, to have more accurate sensors, the designer has to optimize the structures so as to acquire a narrower reflection spectrum. An alternative method is using PhC fibers [21,22] or using a combination of PhC waveguides and PhC resonators [23]. The basics of the former biosensors are as follows: two PhC waveguide are coupled to a high quality factor resonator. One of them acts as the input waveguide and the other as the output waveguide. Such a topology acts as an ultra-low-bandwidth optical filter. The sampled tissue is placed on the resonator. The difference in the dielectric constant of the normal and cancerous tissues changes the resonance frequency. If the quality factor is high enough, such a small change causes a considerable change in transmission spectrum. For cancer detection, in an ideal sensor a 100% transmittance should occur for normal tissue and zero transmission should happen for cancerous cells. Such methods have been experimentally proven to be able to detect different types of cancer cells [24–27]. Such nano-cavity coupled PhC waveguides have been also proposed for the detection of simultaneous cancer types [28].

Although using high Q-factor resonators creates very sensitive devices, but fabrication of such ultra-sharp filters has its own predicaments. To detect cancerous cells from normal cells, these sensors should

---

* Corresponding Author.
E-mail address: danaie@semnan.ac.ir (M. Danaie).

https://doi.org/10.1016/j.photonics.2018.06.004
Received 3 December 2017; Received in revised form 10 June 2018; Accepted 11 June 2018
Available online 25 June 2018
1569-4410/ © 2018 Elsevier B.V. All rights reserved.

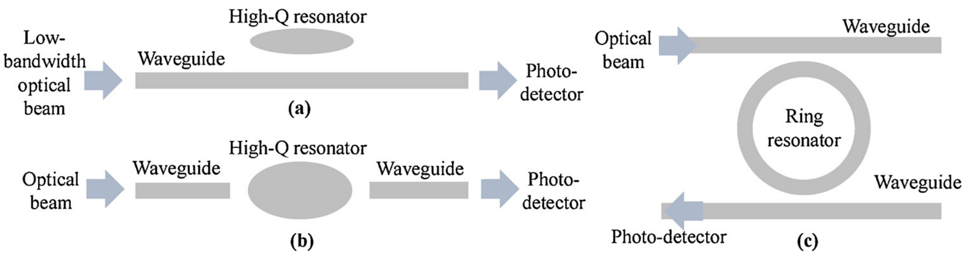

Fig. 1. Most common optical topologies used for designing PhC biosensors, (a) a cavity side-coupled to a waveguide, (b) waveguide-resonator-waveguide topology, (c) ring resonator-based filters.

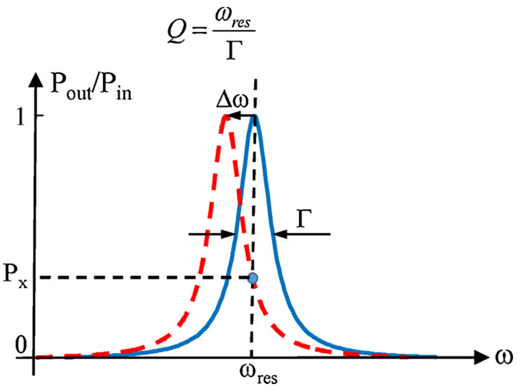

Fig. 2. Solid line the Lorentzian resonance of a cavity (solid line) and shifted resonance due to refractive index change.

be able to detect a refractive index change on the order of ± 0.01. In such any slight variation in shape or of the resonator creates a resonance wavelength shift. Since PhC are usually composed from circular defects, any variation in the radii of these defects can affect the reliability and repeatability of the circuit [29]. Such errors can be disastrous for the cavities used for bio-sensing. Nevertheless, using highly accurate lithography increases the cost of producing such sensors.

In this paper a resonator coupled waveguide filter is proposed for sensing the refractive index. As an application, it is shown that the proposed sensors can be used for the detection of basal cell cancer. Measuring the refractive index of tissues is a topic of interest in bio-optics. The refractive index of human cell has been comprehensively measured and reported in tissue optics books [30]. The human tissue can be modelled using a mixture of water and organic compounds. For example, the skin tissue is comprised of approximately 70% water and 30% protein [30]. For near infrared region (NIR) the following values are estimated for different sections of a cell: cytoplasm: 1.360–1.375, nucleus: 1.38–1.41, extracellular fluid: 1.35:1.36, melanin: 1.6-1.7. Cancerous cells have more protein in their cytoplasm, therefore they have a higher refractive index [31]. For normal and cancerous basal cells, the refractive indices of the cytoplasm are equal to 1.36 and 1.38 respectively [31,32]. Good contrast between the refractive index of normal tissue and basal cell carcinoma has also been reported in THz region [33]. The average refractive index calculated for cytoplasm of a normal cell is 1.360 ± 0.004 for NIR region [34]. Therefore, the separation between normal and cancerous cells is wide enough for the proposed sensors to provide an acceptable distinction.

To diminish the effect of lithography error we have tried to increase the size of the cavity and instead of increasing the Q-factor of the resonator, we have tried to confine the resonance profile of the cavity on the region were the refractive index changes the most. Fairly high sensitivities of 720 and 638 nm/RIU is obtained in this paper. The rest of this paper is as follows. Section 2 reviews the topologies and mechanisms used for design of optical biosensors. Section 3 discusses the first proposed senor, while Section 4 introduces the second topology. Sensitivity analysis is performed in Section 5. Section 6 summarizes the results and compares them with the results reported in the literature. Finally, the last section is devoted to conclusions.

2. Photonic crystal biosensors based on optical resonators

Different mechanisms for designing biosensors have been proposed in the literature. Fig. 1 summarizes the most common topologies. Such topologies include high Q-factor resonators side coupled to a waveguide (Fig. 1(a)), two waveguides coupled through a single resonator (Fig. 1(b)) and ring resonators (Fig. 1(c)).

These topologies act as narrow-band optical filters. When the cavity is subjected to the analyte, the refractive index variation of the analyte changes the optical response of the filter. Based on the perturbation theory, when the material within a cavity is subjected to a small change, the corresponding resonance shift can be calculated using the following formula [35]:

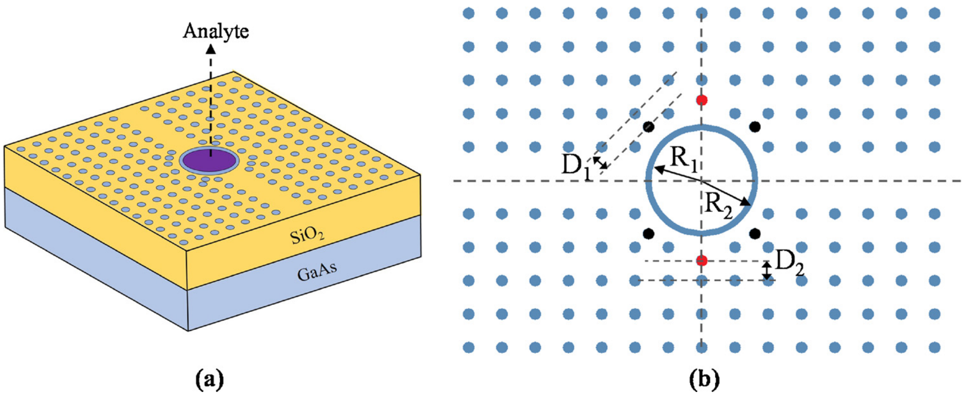

Fig. 3. The proposed PhC biosensor topology based on two waveguides and a ring, (a) 3D view (b) top view. R_1, R_2, D_1 and D_2 are equal to: 1.5a, 1.7a, 0.57a and 0.6a respectively, where “a” is the lattice constant equal to 410 nm. The rest of rods have a radii equal to 0.182a.

Download English Version:

https://daneshyari.com/en/article/7932738

Download Persian Version:

https://daneshyari.com/article/7932738

Daneshyari.com