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An ultrasensitive optical label-free polymeric biosensor based on concentric triple microring resonators with a central microdisk resonator

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ABSTRACT

In this paper we propose an optical label-free biosensor based on a polymeric platform. Label-free biosensors have not the drawbacks and stability problems of commercialized devices which are used for detection of labeled molecules. In addition, we choose polymeric platform, due to simple and low cost fabrication process and also high biocompatibility properties. The suggested structure consists of concentric triple ring resonators along with a disk resonator which offers deeper notches, higher sensitivity and vaster detection area with respect to other similar configurations such as single ring resonator, double concentric ring resonators, etc. Our numerical simulations based on the finite difference time domain (FDTD) method, show that in optimized structure, a transmission notch depth of -48.7 dB for sensor at rest and a free spectral range of 56 nm are achievable. In addition, resonance wavelength sensitivity and output power sensitivity of sensor are 1000 nm/RIU and 1.8×10^4 dB/RIU, respectively. The external radius of outer ring resonator is only 5 μm, and detection area of the sensor is 40.37 μm^2. With this small size, to the best of our knowledge, the obtained notch depth and sensitivity parameters are one of the highest values in ring resonator-based biosensors reported to date.

1. Introduction

In the last decade, biosensors and chemical sensors have attracted considerable attention due to their wide application potential in the fields of medical diagnostics, drug development, food quality control, environmental monitoring, and homeland security [1]. Among various kinds of biosensors, planar integrated photonic ones, become more and more important because of distinct advantages. Features of optical sensors such as tiny size, protection from electromagnetic interference, simplicity of multiplexing using wavelength encoding, and capability of remote sensing, provide more substantial advantages than electrical transducers [2,3]. Furthermore, photonic biosensors have ability to be integrated with other photonic, biochemical and microfluidic components; therefore implementation of lab-on-a-chip is feasible [1].

In general, optical biosensors can be categorized into two main groups: sensors based on traditional fluorescence detection methods and label-free biosensors. Fluorescence-based detection methods are time wasting, labor and expensive [4]. These methods are based on biomolecules tagged with fluorescent, radio or enzymatic labels which may alter real nature and properties of molecules [5]. On the contrary, label-free biosensors do not use any kind of label. In other words, they use direct detection techniques that avoid any kind of damage or contamination to the analyte. In direct detection methods, target molecules are attached on the surface of sensors and process of detection will be done by measuring the optical characters alterations. Label-free biosensors permit the biomolecules to be sensed in a natural way, so the complexity, pollution and cost of detection process are reduced. Hence optical label-free biosensors have received attention in the context of biomolecular detection.

To implement integrated lab-on-a-chip, silicon is a proper candidate that provides high sensitivity biosensors. Therefore, in recent years silicon photonics has had rapid development with great investment. However, it seems that further diminishing the cost of integrated photonic devices would still be needed. Among different materials, polymers have lower cost than others, so they are attractive for manufacturing of photonic devices [6,7]. Polymeric sensors have less sensitivity than silicon equivalents, but their sensitivity can be enhanced by adding nanoparticles [8]. Despite low cost, polymers have other advantages. They have

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unique optical, electrical, thermal and magnetic properties. Biomaterials such as enzymes and antibodies can be embedded into the polymer matrix to create powerful interactions, which result in highly biocompatible devices. Also polymeric materials are light, flexible, and they can be easily processed electrochemically and chemically. Because of above-mentioned characteristics, polymers have been used as a suitable alternative to other materials utilized in biosensors having low detection limits [9–14].

There are several approaches to design of integrated optical label-free biosensors, such as surface plasmon resonators [5,15,16], interferometers [17,18], optical fibers [19,20], photonic crystals [21–24], and optical microresonators [3,4,25–44]. In recent years, ring resonators have become popular for offering optical biosensors with high sensitivity and small size as compared to other approaches. Flueckiger and his colleagues presented cascaded SOI microring resonators for detection of biomolecules in PDMS microfluidic channels with sensitivity of ~40 nm/RIU [25]. Khorasaninejad et al. proposed and analyzed novel ring resonator based bio-chemical sensors on silicon nanowire optical waveguide (SNOW) with sensitivity of 243 nm/RIU [3]. Vos et al. demonstrated an optical biosensor based on microring cavities in silicon-on-insulator (SOI) with sensitivity of 70 nm/RIU that fits in an area below $10 \times 10\ \mu m^2$ [35]. Oh et al. suggested an ultra-sensitive integrated photonic structure using an InP-based triangular resonator, in which a surface plasmon resonance (SPR) gold film was applied on a total internal reflection mirror. They analyzed and optimized their structure and a significantly enhanced sensitivity of 930 nm/RIU was obtained at a certain condition of structure [36]. Gylfason et al. presented the design, fabrication, and characterization of a packaged array of individually addressable slot-waveguide ring resonator sensors in a compact cartridge. They achieved a refractive index sensitivity of 246 nm/RIU for this sensor [37]. A slot-waveguide-based ring resonator in SOI with a footprint of only $13 \times 10\ \mu m^2$ proposed by Claes et al. [38]. Results of their experiments showed sensitivity of 298 nm/RIU. In other work, the authors presented a sensor that consists of two cascaded ring resonators with 2.5 mm physical roundtrip length, which works analogously to a Vernier-scale. They experimentally determined the device sensitivity to be as high as 2169 nm/RIU in aqueous environment [39]. Li et al. reported a label-free biosensor based on concentric microring resonators in SOI platform. The bulk detection sensitivity of 683 nm/RIU was obtained with an area of $27.646\ \mu m^2$ [40].

In spite of high sensitivity biosensors provided in recent years, it seems further reducing of their cost and size is still needed. In this work, we propose an optical label-free microresonator biosensor. The numerical simulations based on the finite difference time domain (FDTD) method show the effective enhancement of notch depth and increasing the sensitivity of the proposed sensor.

2. Sensing mechanism of ring resonator sensor

Our proposed sensor is based on concentric coupled microresonators. To describe sensing mechanism of the proposed structure, a basic configuration, which consists of unidirectional coupling between a ring resonator and a bus waveguide, is described in Fig. 1(a). The parameters α, κ and t are loss coefficient of the ring, coupling coefficient between the ring and waveguide and transmission coefficient in the bus waveguide, respectively. Resonance status appears when the phase change in a round-trip is equal to $2m\pi$, where m is an integer. The resonant wavelength is given by [45]

$$\lambda_{res} = n_{eff}\frac{L}{m}, \tag{1}$$

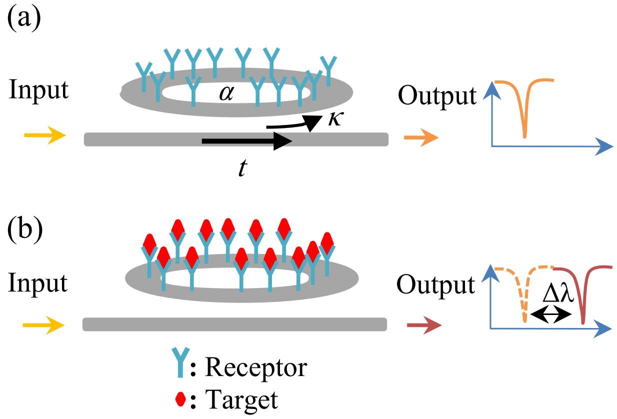

Fig. 1. Schematic of an optical biosensor with resonance spectrum. (a) Biosensor response in rest state, and (b) spectrum shift induced by targets binding to receptors.

where n_{eff} is the effective refractive index of propagation mode, L is the perimeter of the ring, and m is an integer value to indicate mode number. The resonant wavelengths are highly dependent on the effective index alteration of the guided mode. The effective index variation is created by presence of biomolecules such as antibodies and enzymes on the surface of sensing areas [46]. In microresonator-based biosensors, for detecting the specific target, the resonator surfaces have receptors with immobilized binding places. These receptors react in a special way only with the analyte, so that the analyte molecules remain joined to the surface. Fig. 1(b) shows the operating principle of a sensor for biological detection. Light travels through a waveguide within the microchip sensor. Interaction of target agents with antibodies immobilized on the sensing region, results in alteration of effective refractive index and the wavelength of transmitted spectrum.

3. Proposed structure and simulation results

In this paper, a novel optical biosensor is suggested based on concentric ring resonators and a disk resonator. Li et al. previously compared the operation of two biosensors based on single ring (SR) and double concentric ring (DCR) structures [4]. They observed that the output signal in DCR biosensor had deeper notch compared with output spectrum in SR biosensor. Increasing notch depth and being sharp transmission wave enhance sensitivity of a biosensor.

Fig. 2 shows our proposed structure with outer radius of 5 μm for external ring. This biosensor consists of concentric triple ring

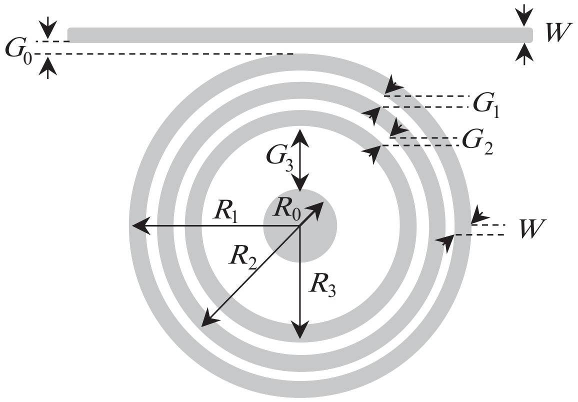

Fig. 2. Structure of the proposed biosensor. All parts including straight waveguide, concentric microring resonators and central microdisk resonator are in polymer.