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Original research article

Asymmetrical microring resonator based on whispering gallery modes for the detection of glucose concentration

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ABSTRACT

The optical resonator based on whispering gallery modes (WGMs) was widely studied due to its application potential in many fields. The novel asymmetrical microring resonator was proposed and investigated numerically using finite-difference time-domain (FDTD) method in this paper. The asymmetry of the asymmetrical microring resonator structure was reflected in the material and the structure of the microring resonator. The *Q* factor of the proposed asymmetrical microring, which was a significant parameter to measure the performance of microresonators, was more than five times of conventional microring resonator while maintaining the same sensitivity. The simulation verified that the structure can be applied to the detection of glucose solution concentration. This provided the potential for high-performance microring resonator to integrate on chip-scale devices for biosensing.

1. Introduction

The sensor was the eyes of human that quantitatively analyzed the microscopic external component. With the rapid development of the field of medical chemistry, the research of biosensors has received more attention. Integrated optical biosensors have been extensively studied for their miniaturization and ease of integration to microfluidic or electronic devices [1]. Optical microcavity based on the whispering gallery mode (WGMs) was a special kind of resonant optical sensor and had a bright future in the field of biosensing [2]. As the majority of scientific research workers studied the microcavity based on WGMs, many excellent research results have been presented [3–6]. There was no doubt that microsphere, microdisk, and microring were the most studied as classic microcavity structures. Quality factor (*Q*) and Sensitivity (*S*) were important indicators to measure the performance of optical microcavity biosensors. Therefore, researchers hoped to obtain high-*Q* and high-sensitivity microresonators. Gorodetsky et al. [7] demonstrated that the quality factor (*Q*) of the microsphere structure can reach 10^{10} at 633 nm. Asymmetric microsphere resonators were fabricated from optical fibers which support dynamical tunneling to excite high-*Q* WGMs [8]. Hybrid microsphere resonator was further enhanced due to the plasmonic effect [9]. The WGMs microsphere resonators were favored for their ultra-high *Q*, however its three-dimensional (3D) structure limited its small-scale on-chip integration. In contrast, microdisks and microrings had more advantages in structure. Soltani et al. [10] reported an ultra-high *Q* microdisk resonator in a silicon-on-insulator (SOI) platform from fabrication and experimental characterization. High quality ($Q \approx 6 \times 10^5$) microdisk resonators were fabricated using Si_3N_4 at wavelength of 652–660 nm and wrap-around coupling waveguides were integrated in-plane to enable critical coupling to specific microdisk radial modes [11]. A.Ramachandran et al. [12] successfully explored a system based on optical microring resonator for quantitative and qualitative biosensing applications. Ciminelli et al. [13] investigated different SOI microring resonator for glucose

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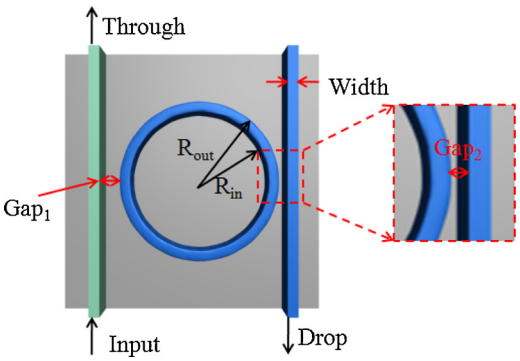

Fig. 1. Schematic structure of the proposed asymmetric microring resonator.

biosensing and the order of *Q* factor up to 10^5. It should be noted that the goal of achieving single-molecule detection using an optical biosensor based on WGMs had been achieved [14–17]. At the same time, many researchers still worked hard to improve biosensor performance mainly from two aspects of microcavity structure and material properties. Gabalis et al. [18] designed and simulated the new type of perforated microring resonator, which improved the detection sensitivity of traditional microring resonator. Li et al. [19] proposed a concentric double-ring micro-resonator, which was promising for the detection of single strand DNA and double strand DNA. Zou et al. [20] fabricated chalcogenide glass microring resonator using the technology of resist-free single-step thermal nanoimprint and obtained ultra-high *Q* near 1550 nm wavelengths. However, few people improved the performance of optical microcavities from both the microcavity structure and material simultaneously.

In this paper, we proposed an asymmetrical microring resonator start from two aspects of microcavity structure and material at the same time. It was worth noting that the asymmetry was manifested in two aspects: structural asymmetry and waveguide material asymmetry. Compared with conventional microring resonators with the same size, the improved microring resonator had similar detection sensitivity and more than five times of Q factor which was a significant parameter to measure the performance of microresonator. Our simulations demonstrated the detection of glucose solution by this device, indicating its good application prospects in biosensing.

2. The asymmetric microring resonator and detection principle

The model proposed in this paper was investigated numerically using finite-difference time-domain (FDTD) method [21,22]. The Schematic structure of the proposed asymmetric microring resonator was shown in Fig. 1.

The resonator consisted of two coupled straight waveguides and a microring cavity. The width of the waveguide in the resonator was defined as *Width*. The outer radius of the ring cavity was R_{out} and the inner radius was R_{in}. The relationship between the radius and the waveguide width can be expressed as $Width = R_{out}\text{-}R_{in}$. The gap between the input straight waveguide and the ring cavity was denoted as Gap_1, and the coupling gap between the ring cavity and the output straight waveguide was defined as Gap_2 shown in the inset of Fig. 1. The ambient refractive index of the asymmetric microring resonator was set as 1.3101, representing a glucose solution with concentration of 0 g/l. The asymmetry of the asymmetrical microring resonator structure proposed in this paper was reflected in two aspects: The first aspect was the asymmetry of the material in the microcavity. The materials of the input straight waveguide of the microring resonator and the ring cavity with output straight waveguide were selected with different refractive index. The refractive index of the input straight waveguide was denoted as n_1, the refractive index of the ring cavity and the output straight waveguide was denoted as n_2, and the relationship among the refractive index of the ring cavity with the output straight waveguide, input straight waveguide and the ambient was $n_2 > n_1 > n_s$. The second aspect was reflected in the structure of the microring resonator. The gap (Gap_1) between the input straight waveguide and the ring cavity was different with the gap (Gap_2) between the output straight waveguide and the ring cavity.

Light of a specific wavelength can be propagated in the waveguide due to total reflection of light [23]. The incident light was input from the *Input* port. Through the input straight waveguide, a part of the light that satisfied the resonance condition was coupled into the ring cavity, and part of the light was output through the *Through* port. The light coupled into the ring cavity resonated within the ring waveguide, and part of resonant light waves coupled into the output waveguide was output at the *Drop* port and received by the testing device.

In order to measure the performance of the proposed asymmetrical microring resonator, the quality factor (*Q*), sensitivity (*S*) and figure of merit (*FOM*) were analyzed in this paper. The *Q* of the given device represented the photon lifetime within the resonant microring. At the same time, the resonant spectrum of the resonator with high *Q* factor had a narrower line width, which facilitated the analysis of small shift of resonance peak due to a small change in refractive index induced by the analyte. The *Q* factor can be expressed by [24]

$$Q = \frac{\lambda_{res}}{FWHM} \tag{1}$$