Proposal of a Hybrid Optical Double Ring Resonator for Cancer Biosensing

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Abstract: A new design for a silicon-on-insulator (SOI) optical biosensor is proposed in the form of a hybrid double-ring resonator. The proposed device improves the sensitivity by 2.4 times compared with the traditional devices.

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1. Introduction

A real-time with extraordinary accuracy diagnosis is required nowadays. The demand of fabricating a robust biosensor which fulfills this requirement with a small footprint is increasing every day [1]. Disease diagnosis, especially cancer, at its initial stage can save many lives. Most types of sensors are limited in sensitivity and resolution. However, optical sensors introduce a very good sensitivity with real-time detection [2].

Optical sensors have gained significant interest nowadays especially in the biomedical field which is related to sensing biological and chemical samples. Among various types of optical sensors, those based on silicon-on-insulator (SOI) are more attractive to biosensing. Indeed, SOI-based sensors are characterized by low cost, small footprint, and high mass production [3]. The main reason for these merits is their compatibility with complementary metal oxide semiconductor (CMOS) technology, allowing the fabrication of photonic sensors with electronic circuits on a single chip. Photonic crystals, disk resonators, bragg gratings, strip waveguide, and waveguide ring resonators (RR) are some types of SOI-based sensors [4]. Among these types, RR provides fast response and precise analysis of various substances [5].

The identification of the disease can be determined by RR through a shift in the resonance wavelength. When the evanescent field of the resonating light interacts with the cancer samples, the light behavior change leads to a change in the effective refractive index. This change in refractive index causes a resonance wavelength shift [6]. That is, increasing the amount of evanescent field leads to an increase in the light bio-sample interaction. This results to higher sensitivity as well as higher optical losses. The sensitivity can be controlled by the design of the waveguide. A slot waveguide provides higher sensitivity than strip one, but the latter has lower losses than the first one [7].

In order to find an optimal solution for this trade-off between low optical losses and high sensitivity, a hybrid design between strip and slot waveguides has been proposed in [3]. However, it increases the area of the conventional waveguide by 27.2 times, achieving only 35% of the slot-waveguide sensitivity. This increase in RR's area leads to a sensor with larger size and higher cost.

According to the best of our knowledge, there is no study that shows the effect of a hybrid design using a double-ring resonator. In this paper, we propose a new design for hybrid-waveguide (strip- and slot-waveguides) using a double-ring resonator. In our performance analysis, we keep the same area of the previous conventional waveguide so that the cost of the sensor is fixed. Our proposed design improves the sensitivity with 2.4 times that of traditional waveguides. Specifically, our design of the hybrid-waveguide has a sensitivity of 86% of that of slot-waveguide, while previous designs have achieved a sensitivity of only 35% of the slot-waveguide.

2. Proposed Design

In this paper, an SOI system is designed with buried oxide layer (BOX) height of 4 μm. A strip silicon (Si) waveguide, in the form of a double-ring resonator, is used with 0.4 μm width, 0.22 μm height inside insulator layer, and 0.22 μm height above BOX. The parameters for the proposed double-ring resonator are as follows. The radius of the ring is 3.1 μm and the gap between the ring resonator and the waveguide is 0.1 μm. The gap inside the slot-waveguide and hybrid-waveguide is 0.1 μm. Figure 1 shows the three different devices according to the type of waveguide. In this figure, the red arrow indicates the direction of the light source, and the green arrow indicates the position of the light detector. It is clear that the area of the proposed waveguide is the same as the area of the conventional waveguides. The proposed device is shown in Fig. 1(c).

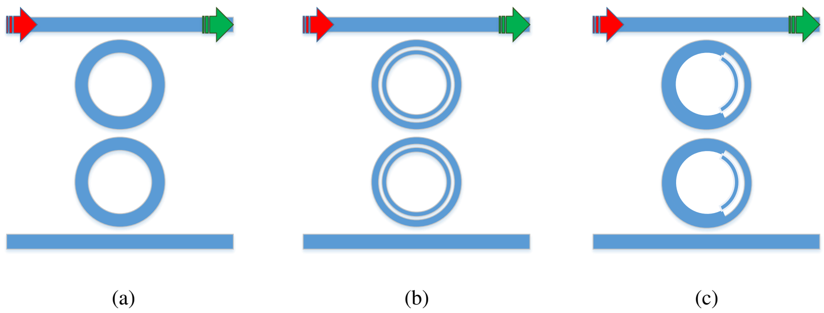

Fig. 1: Schematics of different double-ring resonators based on waveguide types: (a) Strip-waveguide. (b) Slot-waveguide. (c) Hybrid-waveguide, consisting of both slot- and strip-waveguides.

3. Performance Analysis

The sensitivity S of the shown designs can be calculated from [7]:

$$S = S_{wg} S_{rr} = \frac{\Delta n_{\text{eff}}}{\Delta n_{\text{clad}}} \frac{\Delta\lambda}{\Delta n_{\text{eff}}} = \frac{\Delta\lambda}{\Delta n_{\text{clad}}}, \tag{1}$$

where S_{wg} is the waveguide sensitivity, S_{rr} is the sensitivity of ring resonator, Δn_{eff} and Δn_{clad} are the changes in the effective and cladding refractive indices, respectively, and $\Delta\lambda$ is the resonance wavelength shift. This change in the resonance wavelength occurs due to the presence of a cancerous cell in contact with the sensing area of the biosensor, leading to a change in the effective refractive index. Each type of cancer disease has a certain refractive index as listed in Table. 1.

Table 1: Refractive Index (RI) of Biosamples [4].

Name of Biocell	Disease	RI	Name of Biocell	Disease	RI
Normal		1.350	PC-12	Brain Cancer	1.395
Jurkat	Leukemia	1.390	MDA-MB-231	Breast Cancer	1.399
HeLa	Cervical Cancer	1.392	MCF-7	Breast Cancer	1.401

To estimate the performance of the proposed design, the optical quality factor Q is determined from [7]:

$$Q = \frac{\lambda_{res}}{\text{FWHM}}, \tag{2}$$

where λ_{res} is the resonance wavelength and FWHM is the full wave half maximum. In addition, the intrinsic limit of detection *iLOD* is found from [7]:

$$iLOD = \frac{\text{FWHM}}{S}. \tag{3}$$

4. Results and Discussion

Figure 2 shows the output transmission of the three designs representing the different types of waveguide with a zoom curve for each one to clearly notice the shift in resonance wavelength. This shift in resonance wavelength is caused by the change in refractive index due to the presence of cancerous cell.

Table 2 is a comparison between the three designs by evaluation some performance measures, such as sensitivity, quality factor, *iLOD* and FWHM. It is clear that the proposed design has a very good FWHM of 1.8 nm versus 1.4 and 3.7 nm for strip and slot waveguides, respectively. Also, it has the minimum *iLOD* of 0.035, while that of strip- and slot-waveguides are 0.05 and 0.06, respectively. In addition, the proposed hybrid-waveguide introduces a very good sensitivity and quality factor placed between the strip and slot waveguides. Indeed, it has a sensitivity of 50.6 nm which represents 0.85 of that of slot-waveguide and a Q-factor of 864.5 which represents 0.8 of the strip-waveguide Q-factor.

This means that we introduce a new design for a hybrid-waveguide which is a compromise solution between strip and slot waveguides in order to achieve better performance. The strip waveguide has a higher Q but with a low sensitivity. On the other hand, the slot waveguide provides much better sensitivity but with a poor Q. Our proposed system can provide a very good sensitivity side by side with a very good Q.

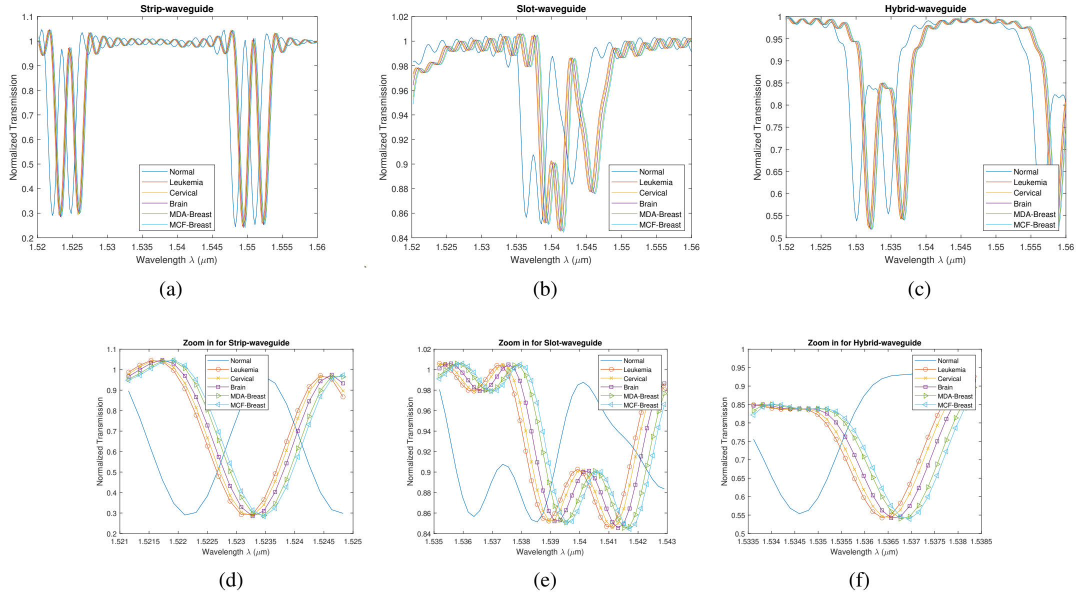

Fig. 2: Transmission spectrum of sensors when using: (a) Strip-waveguide. (b) Slot-waveguide. (c) Proposed Hybrid-waveguide. Zoom in for: (d) Strip-waveguide. (e) Slot-waveguide. (f) Proposed Hybrid-waveguide.

Table 2: Comparison between Proposed Design with Conventional Ones.

Performance measure	Strip-waveguide	Slot-waveguide	Hybrid-waveguide
S [nm/RIU]	28.47	59.15	50.59
Q	1079.51	415.23	864.46
iLOD	0.0495	0.0625	0.0356
FWHM [nm]	1.41	3.7	1.8

5. Conclusion

A new design for a SOI optical biosensor has been proposed in the form of a hybrid double-ring resonator. The device is for detecting cancer disease. The cost and the size of the proposed biosensor is kept the same as that of traditional optical biosensors. We have analyzed and simulated the performance of proposed device and compared the results with that of convectional devices. The performance of the proposed design is shown to be better than that of traditional ones. Specifically, it has the minimum *iLOD*. In addition, it exhibits good results of sensitivity, *Q*-factor, and FWHM. Indeed, it introduces a higher sensitivity than that of strip-waveguide with a larger *Q* than that of slot-waveguide.

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