The sensitivity of sensor based on Microring Resonator (MRR) and Surface Plasmon Resonance (SPR) for diabetes monitoring application

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Abstract. Diabetes mellitus is a disease of metabolic disorders where human blood contains a high amount of sugar level for a prolonged period. This study aims to simulate how effective sensor based on MRR and SPR for the purpose of diabetes monitoring. The results show that sensor based on MRR and SPR provides the ability to detect low level of glucose concentration as low as 7 mmol/L (0.13%) and the ability to detect resonance shift for very small glucose concentration change. Therefore, the sensor based on MRR and SPR can be used for diabetes monitoring. The sensitivity of the sensor based on MRR and SPR is 85.84 nm/RIU and 116.69 °/RIU respectively. These findings are important for the development of diabetes monitoring based on MRR or SPR.

1. Introduction

Diabetes mellitus or famously known as diabetes is a disease of metabolic disorders. Diabetes is a condition where human blood contains a high amount of sugar level for a prolonged period [1]. Diabetes can lead to many horrible conditions such as diabetic ketoacidosis, cardiovascular disease, stroke, chronic kidney disease, and even death [2,3]. Diabetes can be diagnosed by the amount of glucose concentration in blood. The category of diabetes diagnosis can be seen in Table 1.

| Category   | Glucose concentration in blood post-meal |
|------------|-----------------------------------------|
| Healthy    | < 8 mmol/L                               |
| Pre-diabetes| 7.8 – 11.11 mmol/L                      |
| Diabetes   | > 11.11 mmol/L                           |

Table 1. Diabetes diagnosis category [1].
From Table 1 we can confirm how much concentration of glucose in human blood. For example, 10 mmol/L glucose concentration in the blood means that there is 10 mmol or 0.01 mol glucose in 1 L of blood. By multiplying 0.01 mol glucose with the relative mass of glucose we can confirm the mass of glucose in gram scale. By dividing this mass glucose in gram scale with 1L or 1000 ml and then multiplying with 100 we could get the percentage of glucose in the blood [4]. So, it means that 10 mmol/L is equal to 0.18016%. For sensing such an ultra-low-level concentration of biomolecule we need a sensor with very high sensitivity. Sensor-based on MRR or SPR could be used to achieve these goals [5–7]. Therefore, this study is held to simulate how effective sensor based on MRR and SPR for the purpose of diabetes detection.

1.1. Microring resonator
The geometry of MRR consisted of two different types of the waveguide, straight waveguide, and ring waveguide, which interact with each other at a very small distance called gap [8,9]. Figure 1 shows the geometry MRR. Free Spectral Range (FSR) and Quality Factor (Q-Factor) are the main characteristics of MRR which have an important role to know the sensitivity and limits of sensor detection. MRR-based sensors must have large FSR to improve its performance. The greater value of Q-factor the better detection limit resulted and in turn will cause the higher sensor sensitivity [10]. Based on how it works as a sensing device, a light comes through the waveguide then get coupled by the ring and finally produce a resonance [11,12]. Interaction of the MRR with analyte caused a change of MRR waveguide refractive index [13–15]. Thus, the resonance shift occurs. The resonance shift is indicated a change of MRR environment [16].

Figure 1. The geometry of MRR which consisted of two straight waveguides and one ring waveguide.

1.2. Surface plasmon resonance
In the previous study by Miyazaki, surface plasma wave is produced at a metal interface due to the oscillations of charge density at the interface of metal-dielectric, called surface plasmon, and travels along with it, while in both the media a field associated to these waves decays exponentially [17]. Surface plasma waves die out due to non-radiative decay after propagating at a certain length and the dissipated energy has turned the form into heat. As a transverse magnetically (TM) polarized waves, therefore, surfaces plasma waves get excited when the surface plasmons are matches with the wave vector of a beam of TM polarized light incident on the metal-dielectric interface. This phenomenon is what we called as surface plasmon resonance [6]. Figure 2 shows the conventional configuration of Kretschman based surface plasmon resonance. Surface plasmon resonance for the sensor is based on the detection of changes in the metal (gold) refractive index which converted to resonance angle shift [18]. The resonance angle shift is caused by the binding of analytes and ligands in the gold surface [19].
2. Methodology
The finite difference time domain (FDTD) method is generally used for modeling photonic devices. FDTD method provides the ability to calculate both the spatial and temporal properties in a single run, hence these method is very suitable to analyze many structures [20]. FDTD method is used to solves numerical scattering problem and electromagnetic absorption on the basis of Maxwell’s equation based on the Yee Mesh [21]. During this study, Lumerical mode solutions® is used to simulate MRR while Lumerical FDTD solutions® is used to simulate SPR. The initial design of MRR in this study consist of MRR add-drop system based on silicon-on-insulator (SOI) material with waveguide cross-section and ring radius of 500 nm x 220 and 4.5 μm respectively. In the other hand, the initial design of SPR in this study works at 670 nm wavelength and is consist of 3 layers as we can see in figure 2. As for the dimension for each layer are consecutively 50 nm gold layer, 2 nm chromium layer, and 7.95 μm prism (BK7) layer.

We study the response of sensor based on MRR and sensor based on SPR for diabetes monitoring. Therefore, we determine the variation of glucose concentration based on the data of human with diabetes disease in table 1. The glucose concentration of 0 mmol/L (0 %) is used as the baseline point for the simulation. Meanwhile, the glucose concentration of 7 mmol/L (0.13 %) serves as the reference point of healthy human and glucose concentration of 12 mmol/L (0.22 %) and 17 mmol/L (0.31 %) serves as the reference point of human with diabetes disease. In order to check the stability of sensors, we improve the variation for higher glucose concentration, namely 22 mmol/L (0.40 %), 55.5 mmol/L (1 %), 111 mmol/L (2 %), 166.6 mmol/L (3 %), 222 mmol/L (4 %), and 277.5 mmol/L (5 %).

3. Results and discussion

3.1. The response of sensor based on microring resonator for diabetes monitoring
The resonance of MMR occurs when the roundtrip length is proportional to an integer of guided wavelength, hence a constructive interference of light occurs then gives sharp resonance with large intensity [8]. Figure 3 shows the response of a sensor based on MRR for index background of 0 mmol/L (0 %) glucose concentration. The maximum point at the curve provides the resonance peak at the through the port transmission. This curve also serves as the baseline reference to observe the ability of sensor based on MRR for diabetes monitoring.
Figure 3. The transmission of MRR through port point for index background of 0 mmol/L (0 %) glucose concentration.

The presence of glucose analyte in the cladding layer affects the light propagation mode inside MRR waveguides to change [22]. The analyte will absorb the energy from the evanescent field that leaked out from MRR waveguides which causes to decreasing on the phase velocity of propagated light in MRR waveguides. The decreasing on the phase velocity of MRR waveguides induces the value of waveguides effective refractive index to increase [23]. The glucose concentration we used in this simulation resembles glucose levels in human blood. Therefore, we simulated the MRR based-sensor for each variation of the glucose concentration using the finite difference time domain (FDTD) method. Figure 4.a shows that the increase in glucose concentration induces the resonance shift of MRR. The resonance shifts occur for very low glucose concentration change from the baseline point of 0 mmol/L (0 %) to 7 mmol/L (0.13 %), 12 mmol/L (0.22 %), 17 mmol/L (0.31 %), and 22 mmol/L (0.40 %) in figure 4.a has proven the ability of MRR based-sensor for diabetes monitoring. Hence, the resonance shift to larger wavelength occurs. Furthermore, we observed the linearity between the resonance shift and the variation of the cladding layer refractive index in figure 4.b. The sensitivity of MRR based-sensor then can be known by calculating the slope of the linear curve in figure 4.b which proportional to the ratio between the resonance shifts and the refractive index variations of the cladding layer. Hence, the sensitivity of MRR based-sensor in this simulation is 85.84 nm/RIU. The sensitivity of MRR based-sensor is used to define its performance for diabetes monitoring application. The sensitivity is defined as the ratio between resonance shifts and refractive index variations of the cladding layer due to the change of glucose concentration.
3.2. The response of sensor based on surface plasmon resonance for diabetes monitoring

Incident wave 670 nm wavelength is emitted to the surface of the chromium adhesive layer from a light source. The interaction between the incident wave and the surface of the chromium adhesive layer induces an evanescent field on the gold layer. This evanescent field then interacts with plasmon of gold which produces by the interaction between the gold layer and dielectric medium [24]. The surface plasmon wave then generated at the boundary of gold and dielectric layer by the interaction between the evanescent field and the plasmon of gold [19]. The incident wave is swept at the surface of the chromium layer with incident angle 36° to 80°. The resonance of the surface plasmon then occurs at a certain incident angle when most of the incident wave energy is absorbed by the plasmon in the gold layer and turned to the surface plasmon wave [25]. This phenomenon can be detected by the minimum reflectance at the detector. From the curve in figure 5, we can see the minimum point at the response curve of sensor based on SPR for index background of 0 mmol/L (0 %) glucose concentration. The minimum point describes the resonance angle of the sensor based on surface plasmon resonance. This curve also serves as the baseline reference to observe the ability of sensor based on surface plasmon resonance for diabetes monitoring.

Figure 5. The response curve of sensor based on SPR in index background of 0 mmol/L (0 %) glucose concentration.
The increasing of analytic induces the analyte refractive index value itself to increased, hence the resonance angle is shifting to larger angles accordingly to the relation between analyte refractive index and SPR resonance angle in [24]. Figure 6.a shows that the resonance angle shift occurs for each glucose concentration change where 0 mmol/L (0 %) serve as the baseline. The ability of sensor based on SPR for diabetes monitoring has been proved by its ability to show shifting for very small glucose concentration change such as from the baseline point to 7 mmol/L (0.13 %), 12 mmol/L (0.22 %), 17 mmol/L (0.31 %), and 22 mmol/L (0.40 %). In figure 6.b, we analyze the sensitivity value of the sensor based on SPR for diabetes monitoring. The sensitivity of SPR based-sensor can be defined as the ratio of resonance angle shifts to the change of the analyte refractive index [25]. The sensitivity of SPR based-sensor determines its performance for diabetes monitoring application because in this simulation we used approximate glucose concentration to resembles glucose levels in human blood. The sensitivity of the sensor based on SPR in this study is 116.69 °/RIU. Moreover, with the value of 116.69 °/RIU, this sensor based on SPR provides fine performance in which these sensors able to detect such a low level of glucose concentration change.

Figure 6. SPR based-sensor response curve using FDTD approach for (a) various glucose concentration and (b) resonance shift response to refractive index variation at 670 nm wavelength.

4. Conclusion
This study set out to simulate how effective sensor based on MRR and sensor based on SPR for diabetes monitoring. Both types of sensors are providing resonance shift for the variation of glucose concentration for healthy human and human with diabetes disease. In addition, the sensitivity of the sensor based on MRR and sensor based on surface plasmon resonance is 85.84 nm/RIU and 116.69 °/RIU respectively. Therefore, this study has shown that both sensors can be used for the purpose of diabetes monitoring.

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