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# THE EFFECT OF GLUCOSE CONCENTRATION SAMPLE 0 - 1.50% ON THE QUALITY FACTOR OF MICRORING RESONATOR

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**Abstract**

In this work, we present a study of the effect of glucose concentration on the quality factor of the Silicon on Insulator (SOI) ring resonator based on the refractive index sensor made by ion exchange technique. The effect of glucose concentration on the quality factor of the microring resonator is presented. The calculation has been done using the finite difference time domain (FDTD) method for glucose concentration in range 0-1.50% as analytes. Previous studies have shown that glucose concentration has a linear relationship with resonant wavelength and shown that quality factor would decrease by increasing the wavelength. The results show that glucose concentration affects the quality factor of the resonator microring. Increased glucose concentration causes an increase in wavelength resonance so the quality factor will be decreased, therefore the microring resonator can be used for glucose sensing applications.

Keywords: FWHM, Ion exchange, Microring resonator, Quality factor, Wavelength resonance.

## 1. Introduction

Biochemical sensors have become a growing research topic to analyze analytes. There are several applications such as clinical screening, medical diagnosis, food safety, and environmental monitoring [1, 2]. Sensors based on integrated optical waveguides have been shown to have pledge performance of device. Integrated optical waveguides have many interesting properties like low power consumption, quick response, high sensitivity, and low fabrication costs [3, 4]. Optical waveguide sensors reckon on evanescent waves to interrogate the analytes attendance that adsorbed on the sensors surface or in the surrounding area. Optical waveguide-based devices using evanescent wave are applied for a variety of applications [5]. To detect a low concentration and little number of analytes and found an appropriate device, microring resonator (MRR) is needed [6].

Microring resonator is easily integrated optical with photonic waveguides to allow the realization of complex systems as traveling wave resonator formed by bending the waveguide into a circle or racetrack shape [6,7]. Microring resonator has great potential because they can produce high sensitivity with low fabrication costs [4].

One of the important parameters of the microring resonator is a quality factor that represents the amount of field oscillation before the circulating energy is drained to $e^{-1}$ from the initial energy. A measure of resonance sharpness relative to its center frequency is called quality factor. To define the quality factor, the microring is excited to a certain level and the power decay rate is considered. From this point of view, it can be understood that to get a high-quality factor resonance, we must reduce round trip losses and coupling in the directional coupler [8]. High quality factors make microring resonators have high sensitivity so the ability to detect biomolecule concentrations is better [9].

In the previous study, nanoimprinting technique has been used to fabricated polystyrene microring resonators and attest that the wavelength resonance is highly sensitive to the glucose solution concentration, and also the glucose concentration and the resonance shift has a linear relationship [10] so the quality factor would decrease by the increasing the wavelength resonance [11]. Software has been developed based on the finite difference time domain or FDTD method to investigate the leverage of the concentrations to the resonant wavelength shift of polymer based MRR on different frequency distance and quality factor values [12].

In this study, we analyzed the effect of glucose concentration on the quality factor of Silicon on Insulator microring resonator made by Ion exchange technique using Lumerical Mode software (FDTD method). The main purpose of this study is to find the relationship between variations of glucose concentration, refractive index, wavelength resonance, and quality factor.

## 2. Theory

### 2.1. Microring resonator

The microring resonator was first proposed by Marcatili in 1969 to realize a channel drop filter based on planar optical waveguides. Microring resonators have been verified for a wide range of applications in various material systems like Silicon on Insulator (SOI), III-V semiconductors, glasses, and polymers [13]. An optical fiber ring resonator consists of a closed loop waveguide which is combined into one or more waveguide buses [7]. Figure 1 shows a simple microring resonator. The basic resonator ring has been studied by considering the dielectric ring with the smallest refractive index, embedded in the dielectric material. Optical fields are combined into the ring that the reflected state and light will transmit continually at the ring boundary with the smallest refractive index close to the material [14].

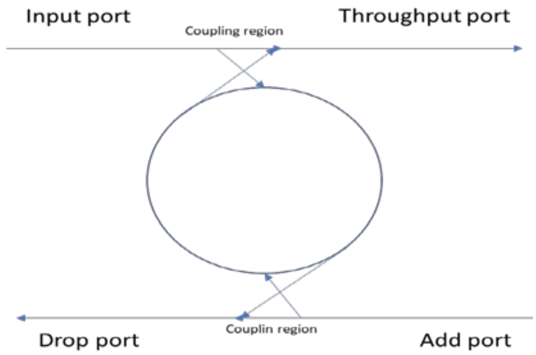



**Fig. 1. Basic model of add-drop single ring resonator filter.**

## 2.2. Parameters of microring resonator

Basically, several parameters can describe the behavior of microring resonators, including:

### 2.2.1. Free spectral range

The frequency distance or spacing between two resonance peaks is called the free spectral range (FSR) [15]. In the wavelength section, FSR can be calculated by the formula given by,

$$FSR = \frac{\lambda^2}{2\pi\, R\, n_{eff}} \quad (1)$$

where $R$ is the radius of the ring, $\lambda$ is light wavelength in vacuum and $n_{eff}$ is the effective refractive index of the waveguide.

### 2.2.2. Full width at half maximum

Another important parameter is the resonance width, which is defined as the full width at half maximum (*FWHM*) [13] that is formulated as follows,

$$FWHM = \frac{\kappa^2\lambda^2}{2\pi^2 n_{eff}} \quad (2)$$

where $\kappa$ is the coupling parameter.

### 2.2.3. Wavelength resonance

Wavelength resonance can be formulated as follows,

$$\lambda_r = \frac{n_{eff} L}{m} \quad (3)$$

where $\lambda_r$ is the wavelength resonance, $L$ is the circumference of the MRR structure, and m is the integer indicating the resonance order [1].

### 2.2.4. Finesse

Another value for the characterization of microring resonator is the finesse (F). This parameter is defined as the ratio of Finesse and width of resonance to certain wavelengths (*FWHM*) [11]. This parameter can be calculated by inserted Eqs. (1) and (2) into the definition. The result is,

$$F = \frac{FSR}{FWHM} = \frac{\Delta\lambda}{2\delta\lambda} = \pi\frac{t}{1-t^2} \approx \frac{\pi}{\kappa^2}; k \ll 1 \quad (4)$$

### 2.2.5. Quality Factor

One of the important characteristics of a microring resonator is quality factor (Q). The quality factor as a wavelength selectivity measure can be defined as the ratio of the power stored for the power dissipated in the ring. It delineates the sharpness of the resonance peak [16].

Quality factors can also be represented as the ratio of energy stored in the resonator to the energy lost per cycle. From this definition, a higher quality factor implies smaller FWHM and lower energy losses, so higher quality factor should lead to better detection limits [1].

The quality factor is given by this formula.

$$Q = \frac{\lambda_r}{FWHM} = \pi\frac{n_{eff}L}{\lambda}\frac{t}{1-t^2} = \frac{n_{eff}L}{\lambda}F \quad (5)$$

The above formula, can be seen that the quality factor of the device is influenced by the microring geometry itself.

### 2.3 Ion Exchange Technique

Ion exchange is a technology for fabricating optical waveguides [17, 18]. Figure 2 shows that ion exchange occurs when relatively moving ions (usually $Na^+$) in glass are pushed by other ions ($Ag^+$) with different size and polarization [19].

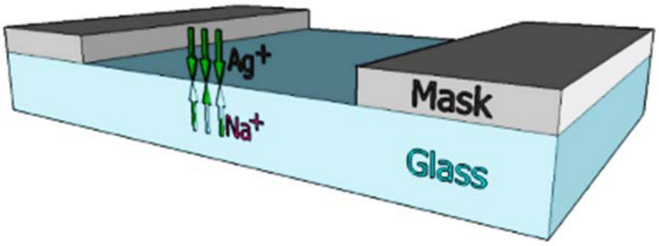



**Fig. 2. Ion exchange configuration (adopted from Amiri [15]).**

Microring resonators created by ion exchange technique shows the highly flexibility to operate in different wavelength windows. The microring resonator featuring high-quality factors is enticing for refractive index sensing [20].

## 3. Materials and Method

We present SOI based on the refractive index sensor. Ion exchange technique is used to make microring resonator based on previous research by Amiri [20]. Ion exchange is one of relatively inexpensive and low loss methods which uses the glass substrates and the salt melt ($AgNO_3/NaNO_3$) at different temperatures and durations can be deposited on the glass substrates [20]. The simulation time and temperature in this study are 1800 fs and 313 K. In this study, we used Silicon (Si) on the waveguide, $SiO_2$ on the substrate. We used glucose concentrations in range 0 - 1.50% and we simulate with Lumerical Mode software as in Fig. 3. The glucose concentration in this simulation used by the following formula below [12],

$$n = 0.2015C + 1.3292 \tag{6}$$

where $n$ is the refractive index of glucose and $C$ is the concentration of glucose in range 0 - 1.50%. For this simulation purposes, we used parameters as shown in Table 1 to simulate in the Lumerical Mode software. Figure 4 shows the flowchart of the microring resonator mechanism for analyzing the quality factor. We used this model for glucose sensing to see that the glucose concentration has a linear relationship with wavelength resonance and the quality factor would decrease by increasing the wavelength resonance.

**Table 1. Parameters used in this simulation.**

| Name | Value |
|---|---|
| **Lc** | 0 |
| **Gap** | 0.1 µm |
| **Radii** | 3.1 µm |
| **Ion-exchange channel refractive index** | 3.444 |
| **Material** | Si (Silicon) - Palik |
| **Base width** | 0.4 µm |
| **Height** | 0.18 µm |
| **Lx** | 25 µm |
| **Background index** | Glucose 0 - 1.50% |
| **Simulation time** | 1800 fs |
| **Simulation temperature** | 313 K |

In this simulation, we varied the variables of glucose concentration, the concentration was 0 - 1.50% using the formula 6 so the refractive index of glucose shown in Table 2. The simulation result of Lumerical Mode will show the calculation using FDTD analysis, as shown in Fig. 2.

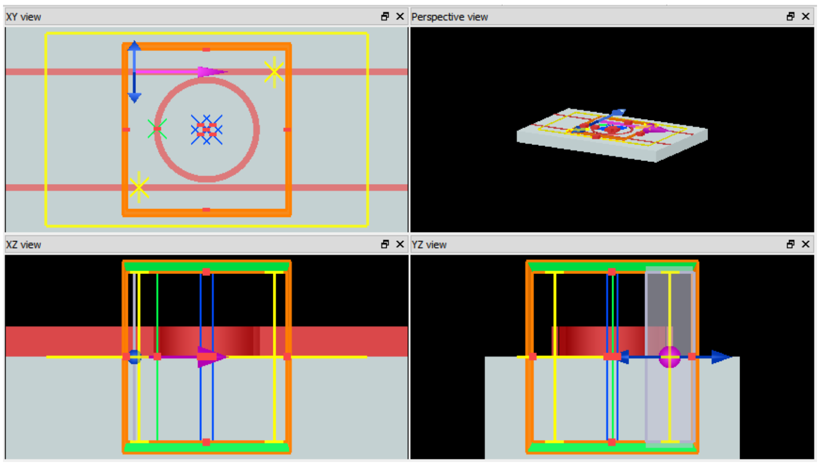



**Fig. 3. Simulation modeling setup of microring resonator.**

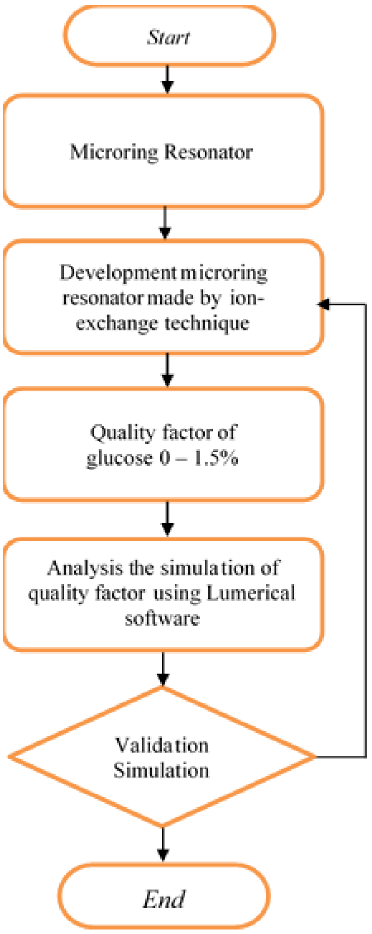



**Fig. 4. Flowchart mechanism microring resonator.**

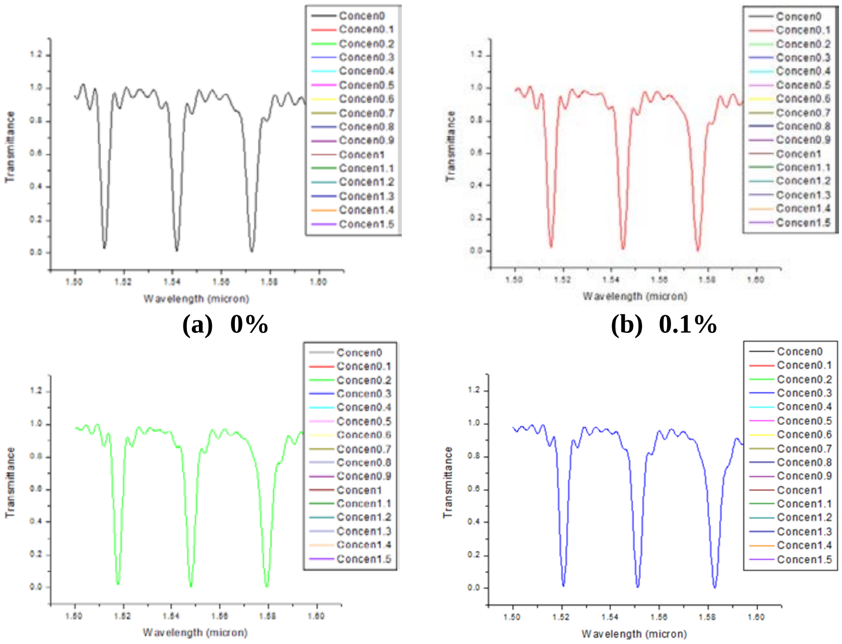
We analyzed the transmittance on the throughput port in Fig. 1 using the FDTD analysis. This was done to obtain transmittance graphics for wavelengths and to obtain wavelength resonance, which used for counting the quality factor of microring resonator.

The refractive index in this simulation has been listed in Table 2. By the consideration of variations in glucose concentration, it has been simulated that the quality factor will decrease with increasing concentration of glucose.

Figures 5, 6, and 7 illustrate the power in throughput port within different glucose concentrations and Fig. 8 shows the tendency of each parameter. In this point, an increase in the concentration of glucose causes an increase in refractive index and wavelength resonance so that the quality factor will decrease. Figures 5, 6, and 7 have the tendency that the wavelength resonance increases with increasing the glucose concentration as listed at Table 3. The effective refractive index of the waveguide mode affects the wavelength resonance of a microring resonator. This index can be influenced by a refractive index change of the surrounding environment that serves as waveguide cladding or biomolecules attached to its surface [10]. To find the *FWHM*, we analyzed every curves in Figs. 5, 6, and 7, the results have been listed in Table 3.

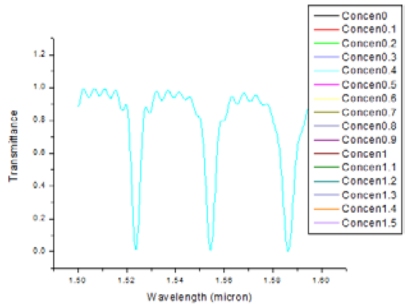
**Table 2. Glucose concentrations in the range of 0 - 1.50% (C) and refractive index of glucose.**

| No. | Concentrations C (%) | Refractive Index |
|---|---|---|
| **1** | 0 | 1.3292 |
| **2.** | 0.1 | 1.3493 |
| **3.** | 0.2 | 1.3695 |
| **4.** | 0.3 | 1.3896 |
| **5.** | 0.4 | 1.4098 |
| **6.** | 0.5 | 1.4299 |
| **7.** | 0.6 | 1.4501 |
| **8.** | 0.7 | 1.4702 |
| **9.** | 0.8 | 1.4904 |
| **10.** | 0.9 | 1.5105 |
| **11.** | 1.0 | 1.5307 |
| **12.** | 1.1 | 1.5508 |
| **13.** | 1.2 | 1.5710 |
| **14.** | 1.3 | 1.5911 |
| **15.** | 1.4 | 1.6113 |
| **16.** | 1.5 | 1.6314 |

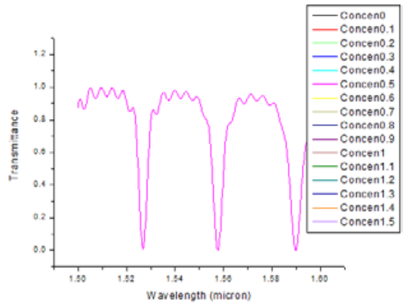



**(a) 0%** **(b) 0.1%**

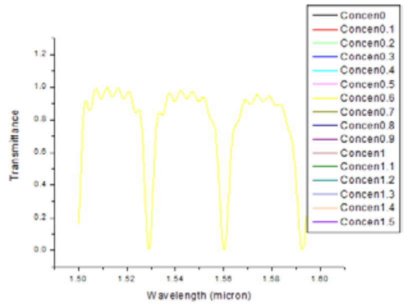
**(c) 0.2%** **(d) 0.3%**



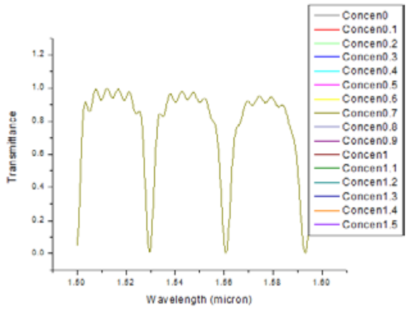

**(e) 0.4%**




**(f) 0.5%**

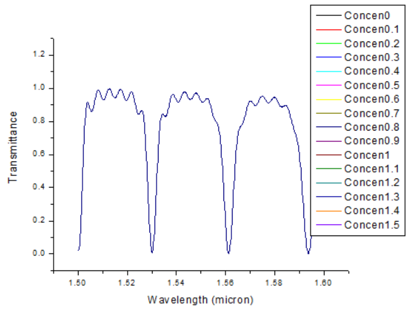



**(g) 0.6%**

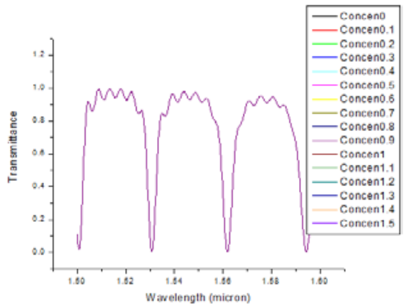



**(h) 0.7%**

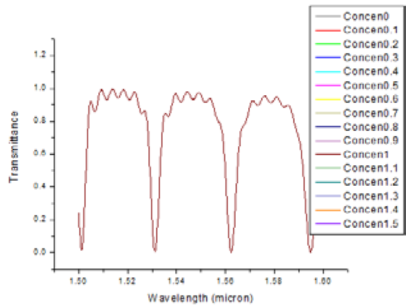
**Fig. 5. Power transmission of glucose concentrations sample 0% to 0.7%.**



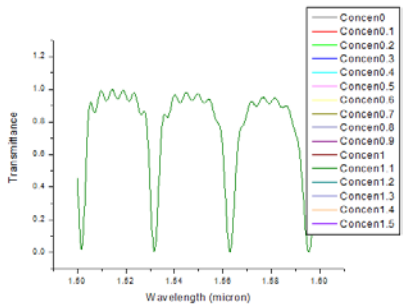

**(a) 0.8%**



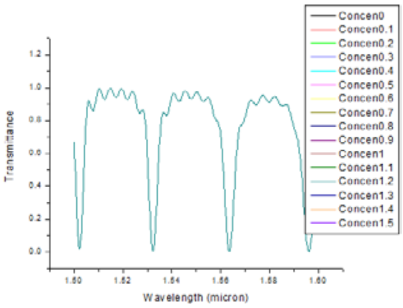

**(b) 0.9%**



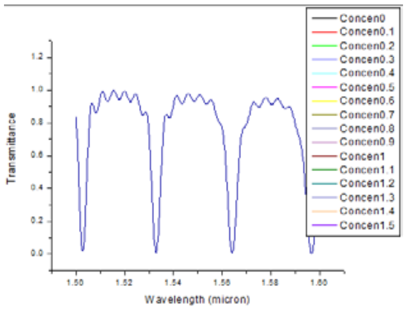

**(c) 1%**



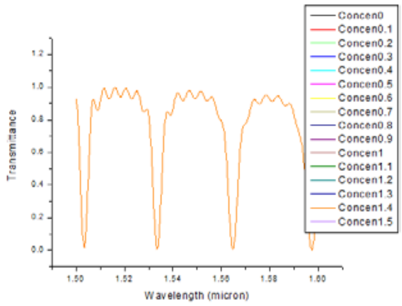

**(d) 1.1%**



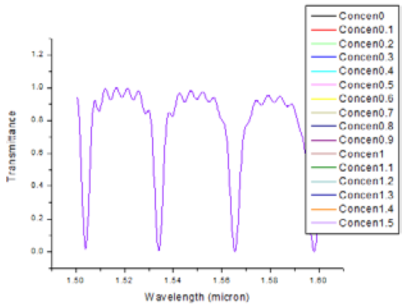

**(e) 1.2%**




**(f) 1.3%**




**(g) 1.4%**




**(h) 1.5%**

**Fig. 6. Power transmission of glucose concentrations sample 0.8% to 1.5%.**

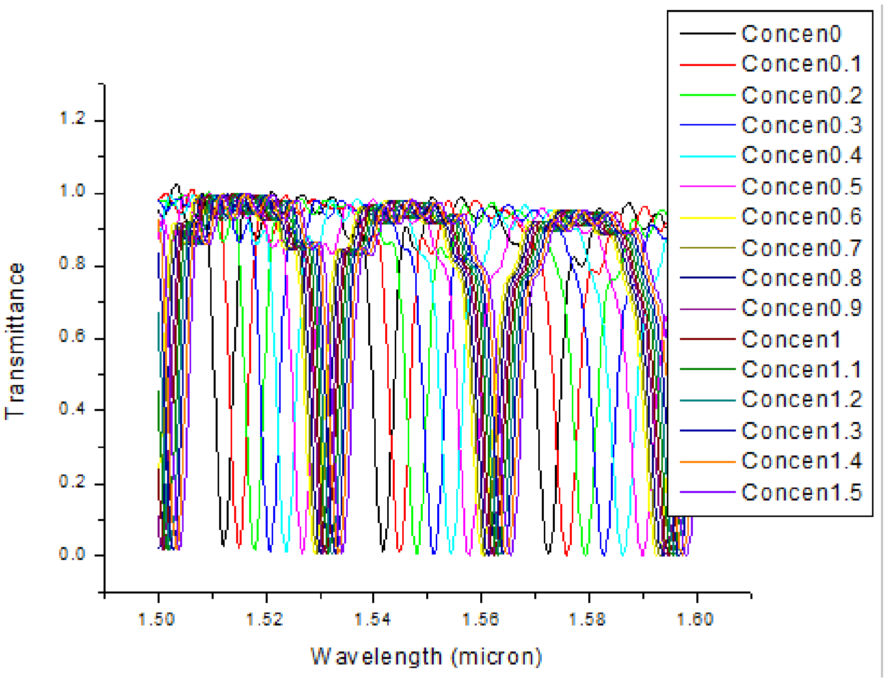



**Fig. 7. Power transmission of different glucose concentrations.**

The quality factor is a comparison between wavelength resonance to *FWHM* so that quality factors can be calculated by equation (5) or $Q = \frac{\lambda_r}{FWHM}$. Information from the analysis results of the graph in Fig. 5(a)-(h) Fig. 6(a)-(h) are the value of $\lambda_{resonance}$ , *FWHM,* and the value of the quality factor listed in Table 3.

**Table 3. List of concentration values, refractive index, and quality factors.**

| Sample shown in Figure | Concentration (%) | $\lambda_{resonance}$ | FWHM ($\mu m$) | ***Quality Factor*** |
|---|---|---|---|---|
| **Fig. 5a** | 0 | 1.542 | 0.402 | 383.21 |
| **Fig. 5b** | 0.1 | 1.545 | 0.414 | 372.90 |
| **Fig. 5c** | 0.2 | 1.548 | 0.415 | 372.66 |
| **Fig. 5d** | 0.3 | 1.551 | 0.444 | 349.45 |
| **Fig. 5e** | 0.4 | 1.554 | 0.462 | 336.44 |
| **Fig. 5f** | 0.5 | 1.558 | 0.463 | 336.468 |
| **Fig. 5g** | 0.6 | 1.560 | 0.475 | 328.467 |
| **Fig. 5h** | 0.7 | 1.561 | 0.474 | 329.25 |
| **Fig. 6a** | 0.8 | 1.5612 | 0.455 | 342.46 |
| **Fig. 6b** | 0.9 | 1.562 | 0.503 | 310.48 |
| **Fig. 6c** | 1.0 | 1.5624 | 0.466 | 335.02 |
| **Fig. 6d** | 1.1 | 1.563 | 0.503 | 310.71 |
| **Fig. 6e** | 1.2 | 1.5636 | 0.493 | 317.15 |
| **Fig. 6f** | 1.3 | 1.564 | 0.483 | 323.83 |
| **Fig. 6g** | 1.4 | 1.5648 | 0.475 | 329.58 |
| **Fig. 6h** | 1.5 | 1.565 | 0.482 | 324.55 |

From Table 3, we can find out the relationship between glucose concentration, the refractive index of glucose, wavelength resonance, and FWHM with quality factor.

The information obtained from the graphs in Figs. 5 and 6 are the values of $\lambda_{resonance}$ differently from each of the glucose concentrations. Each concentration produces different refractive index values according to equation 6. So that it can produce different $\lambda_{resonance}$. Table 3 shows that every increase in glucose concentration, resonant wavelengths increase and Fig. 8(a) shows the tendency of increasing wavelength resonance to concentration. Every increase in glucose concentration, resulting an increase in the refractive index so the wavelength resonance increases. So, the glucose concentration has a linear relationship with wavelength resonance.

Figure 8(b) illustrated that the higher glucose concentration, the greater the value of FWHM. This is caused when the glucose concentration increases, the refractive index value also increases. The increasing refractive index results the wavelength resonance also increasing. This wavelength is quadratic proportional to FWHM. Figure 8(c) shows that the quality factor produced by variations in glucose concentration is different. This is consistent with previous research, which shows that the refractive index of a cladding layer is different even though the refractive index is high or low [20]. The tendency of the graph of simulation result is the quality factors increase when the wavelength resonance increase. Previous research has also proven that when the wavelength increases the value of the quality factor will decrease [11].

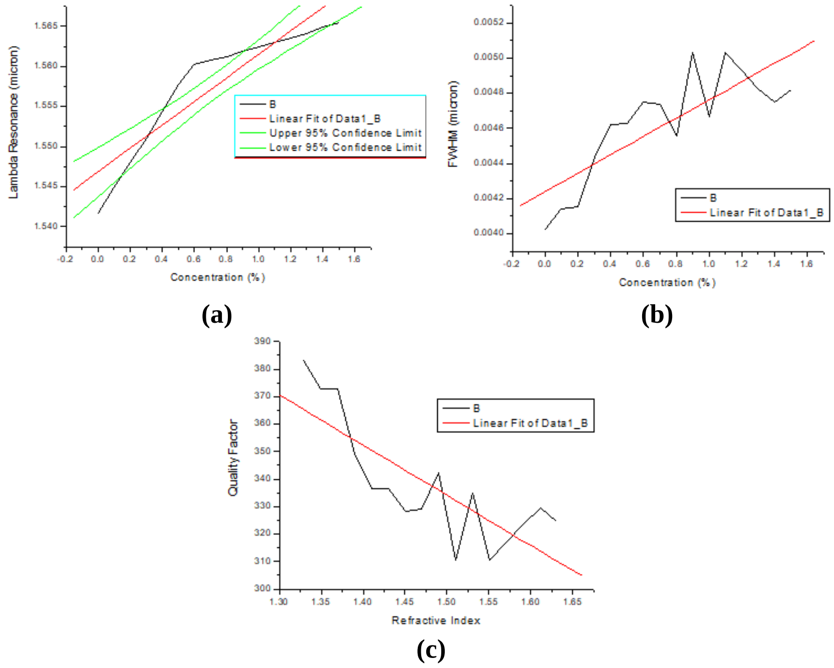



**Fig. 8. The tendency of each parameter. Figures (a), (b), and (c) are wavelength resonance to glucose concentration, FWHM to glucose concentration, and the quality factor to glucose concentration, respectively.**

## 4. Conclusion

This simulation show that glucose concentration affects the quality factor of a microring resonator. The glucose concentration has a linear relationship with wavelength resonance. Increased glucose concentration causes an increase in wavelength resonance so the quality factor will be decreased.

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