

# Micro – ring resonator with variety of gap width for acid rain sensing application: preliminary study

**B Mulyanti<sup>1</sup>, H Ramza<sup>2\*</sup>, R E Pawinanto<sup>1</sup>, J A Rahman<sup>3</sup>, M S Ab-Rahman<sup>4</sup>  
W S Putro, L Hasanah<sup>5</sup>, A B Pantjawati<sup>1</sup>**

<sup>1</sup>Department of Electrical Engineering Education, Universitas Pendidikan Indonesia, 40154, Bandung, West Java, Indonesia

<sup>2</sup>Department of Electrical Engineering, Universitas Muhammadiyah Prof. DR. HAMKA, 12130, Jakarta, Indonesia

<sup>3</sup>Department of Electrical Engineering, Faculty of Engineering, Universiti Industri Selangor, 40000, Shah Alam, Selangor Darul Ehsan, Malaysia

<sup>4</sup>Department of Electronic, Electrical and System Engineering, Universiti Kebangsaan Malaysia, 43600, Bangi, Selangor Darul Ehsan, Malaysia

<sup>5</sup>Department of Physics Education, Universitas Pendidikan Indonesia 40154, Bandung, west Java, Indonesia

E-mail: ramza.harry@gmail.com

**Abstract.** The acid rain is an environmental disaster that it will be intimidates human life. The development micro-ring resonator sensor created from SOI (Silicon on insulator) and it used to detect acid rain index. In this study, the LUMERICAL software was used to simulate SOI material micro-ring resonator. The result shows the optimum values of fixed parameters from ring resonator have dependent variable in gap width. The layers under ring resonator with silicone (Si) and wafer layer of silicone material (Si) were added to seen three conditions of capability model. Model – 3 is an additional of bottom layer that gives the significant effect on the factor of quality. The optimum value is a peak value that given by the FSR calculation.  $FSR = 0$ , it means that is not shows the light propagation in the ring resonator and none of the light coming out on the bus – line.

**Keywords:** Micro-ring resonator, gap width, quality factor, and Free Spectral Range (FSR)

## 1. Introduction

Acid rain is categorized an environmental hazard due to chemical condition in lower atmosphere. The chemical material involved hydrocarbon oxides and nitrogen ( $NO_x$ ) it's very dangerous for human life [1]. In current study of acid rain chemical material, the  $NO_x$  gases sensor were used to detect chemical emission index and calculated with precipitation index [2]. However, the result of calculation  $NO_x$  and precipitation have weakness due to lack of data measurement. Furthermore, to improve the calculation result Cai *et al.* [3] were proposed to develop new sensor using stabilized zirconia and  $MoO_3-In_2O_3$  Nano composites. The highly sensitive using stabilized zirconia and  $MoO_3-In_2O_3$  were improve  $NO_x$  gases sensor and calculation result. In this study, the basic sensor design of ring resonator were developed based optical field [4, 6]. The discrete wavelength, the optical field will mix constructively with another optical fields while both of light running and requiring of extraction conditions from optical representation of optical phase [4, 5]. The optical field from the sensor has highly capability to

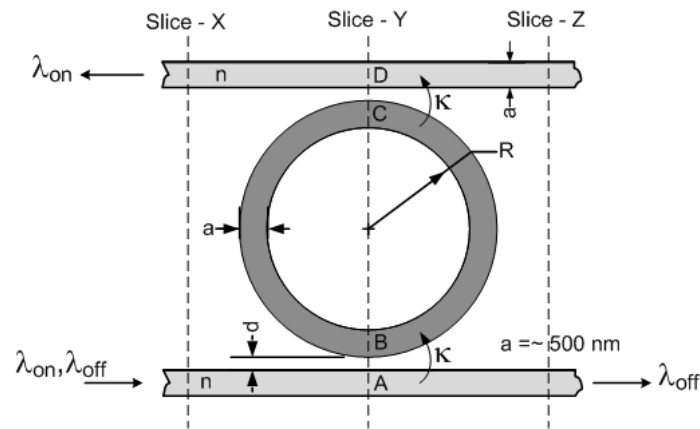


transmit the information NO<sub>x</sub> gases in near future. In this study, we analyze Free Spectral Range (FSR) of micro-ring resonator sensor design by wafer Silicon layer (Si), Silicon Oxide (SiO<sub>2</sub>) Layer and Silicon layer (Si) using LUMERICAL software.

## 2. Methodology

### 2.1. Micro-ring Parameters

Basic of ring resonator can be learnt by considering a dielectric ring that embedded on the dielectric material with smallest refractive index as seen in Figure 1. An optical field is coupled into the ring that it is circumstances and reflection light will transmit continuously on the ring boundaries with smallest refractive index that close to the material [5, 6].



**Figure 1.** Ring dielectric optical resonator

The parameters from a micro-ring resonator is free spectral range (FSR), it is defined as a part of frequency between two sequences of resonance. This case can be approached by following amount of  $m$  and non-dispersive material expressed as;

$$\lambda_m = \frac{2\pi R n_{eff}}{m} \quad (1)$$

$$\Delta f = \frac{c}{2\pi R n_{eff}} \quad (2)$$

In the wavelength part, it is given by,

$$\Delta\lambda = \frac{\lambda^2}{2\pi R n_{eff}} \quad (3)$$

where  $\lambda$  is wavelength at the vacuum space.

The single ring optical resonator with pairing waveguide signal (see Figure 1) in bottom side of signal wave called input bus and the top side is named by output bus. The resonance bandwidth is one of critical parameter for micro-ring and it gives equation,

$$F = \frac{FSR}{\Delta\lambda_{FWHM}} \quad (4)$$

$\Delta\lambda$  is defined as resonance bandwidth (full width half maximum) and it was proved to be,

$$\Delta\lambda = \frac{2\kappa^2 \lambda^2 v_g}{(2\pi)^2 RC} = \frac{2\kappa^2 \lambda^2}{(2\pi)^2 R n_{eff}} \quad (5)$$

$\kappa$  is coupling efficiency that will be discussed further by applying the coupled mode theory, and last expression on the equation (5) produces group of velocity approach ( $v_g$ ) with phase velocity ( $c/n_{eff}$ ), we ignore the dispersive effects for simplifications.

## 2.2. Q – Factor and Transmittance

Quality or Q – Factor for a resonator is a size of frequency structure sensitivity. Q is given by timing of averages energy that stored in every optical path and it is divided by coupling power or output scattering from resonator. Q is limited with radiation and scattering loss. A multi-device functioned from 1.3  $\mu\text{m}$  until 1.5  $\mu\text{m}$  that requires boundary radiation ( $Q$ ) amount 1500 or more for achievement of a width of spectral line is  $\sim 1$  nm or lowest. By inserted equation (5) into the Q – definition ( $Q = \lambda/\Delta\lambda$ ) causes [5, 6],

$$Q = \frac{2\pi^2 R n_{eff}}{\lambda \kappa^2} \quad (6)$$

In fact, Q is an important variable for gives of maximum performance and it will be discussed from alternative at the next part.

## 2.3. Propagation Loss

The different material interface scatters light and causes loss on the each materials and it cannot particularly apply for bent plane waveguide. The wall roughness of waveguide scatters light and loss coefficient is given by Tien's model for a plane waveguide and random roughness distribution expressed [5]

$$\alpha_{st} = 2 \cdot \sigma^2 (n_{eff}^2 - n_0^2) \cdot k_0^2 \cdot \frac{k_x}{\beta} \cdot E_s^2 \quad (7)$$

where  $n_{eff}$  is effective core refractive index,  $n_0$  is cladding refractive index and  $k_0$  is propagation constant in the air,  $k_0 = 2\pi/\lambda$ .  $k_x$  and  $\beta$  are transverse and modal constant propagation respectively,  $k_x = \sqrt{n^2 k_0^2 - \beta^2}$ , then  $E_s$  defined as electric field at the interface between core and cladding.

Generally, when the existing of waveguide on the substrate has equal or greater value of the refractive index, this problem causes leakage of substrate. The bent waveguide, additional leakage occurred cause the existing of radiation loss. Using conformal mapping for planar waveguide solved this problem. The leakage loss  $\alpha$  is expressed by:

$$\alpha = k \cdot e^{-\frac{R}{R_c}} \quad (8)$$

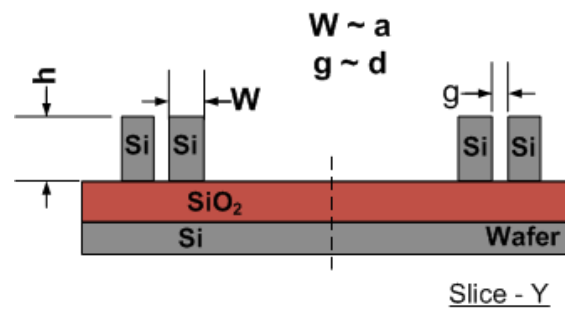
where  $k$  is a constant depend waveguide characteristic,  $R$  is radius of bent waveguide and  $R_c$  is critical radius that is shown with,

$$R_c = \frac{1}{\beta} \left( \frac{n_{eff}}{2 \cdot \Delta n_{eff}} \right)^{3/2} \quad (9)$$

$\beta$  is propagation constant and  $\Delta n_{eff}$  is the different of effective refractive index and effective refractive index of cladding waveguide. In principle, the loss mechanisms can be shown independently.

## 2.4. Micro-ring Parameters

The micro-ring resonator consists of three layers for silicon on insulator (SOI), namely, wafer Silicon layer (Si), Silicon Oxide (SiO<sub>2</sub>) Layer and Silicon layer (Si). This structure is fabricated by initial producing the waveguides through lithography and etching process, then wafer bonding an initial mechanical separation, second and third wafer containing layers that ultimately create the micro-ring resonator (see Figure 2). After wafer bonding, the substrate is detached from the third wafer, and lithography and etching process are used to create the ring resonator [5, 6].



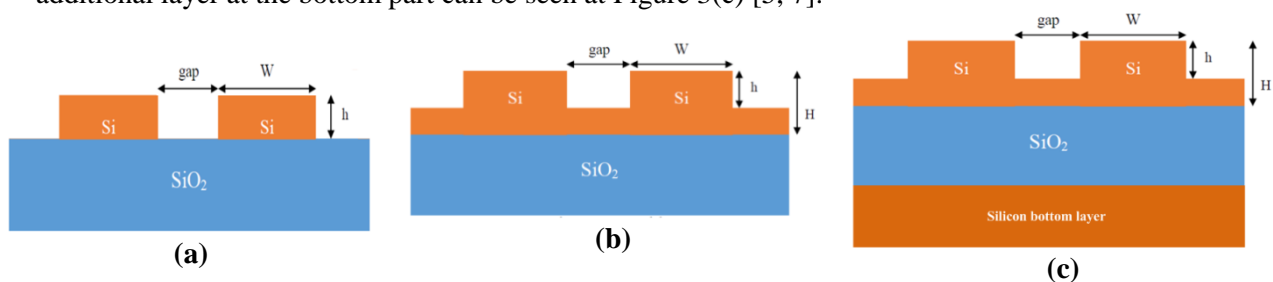
**Figure 2.** Cross section of micro-ring resonator base on slice-y

The parameter of micro ring resonator is determined to look at the beam propagation of signal waveguide. In this simulation study, there are many parameters that are filled to find the best of quality factor (Q). This simulation analysis of micro-ring resonator waveguide uses Lumerical software. As a preliminary study, we were divided into 3-model analysis of micro-ring resonator as seen as Table 1 [7].

**Table 1.** Assuming values of initial parameters for micro-ring resonator

	Symbol	Unit	Model 1	Model 2	Model 3	Remark
Design Expectation						
Wavelength	$\lambda$	nm	1500	1500	1500	For optical communication
Width of Ring	W	nm	500	500	500	
High of Ring	h	nm	220	220	220	
Total of Upper layer	H	nm	0	340	340	
Silicon bottom layer		nm	0	0	500	
Free Spectral Range	FSR	nm	20	20	20	
Result Expectation						
Factor of Quality	Q		5000	5000	5000	Sensor application
Factor of Quality	Q		10000	10000	10000	Better Condition
Free of variable						
Length of gap	g	nm	5 – 200	5 – 200	5 – 200	

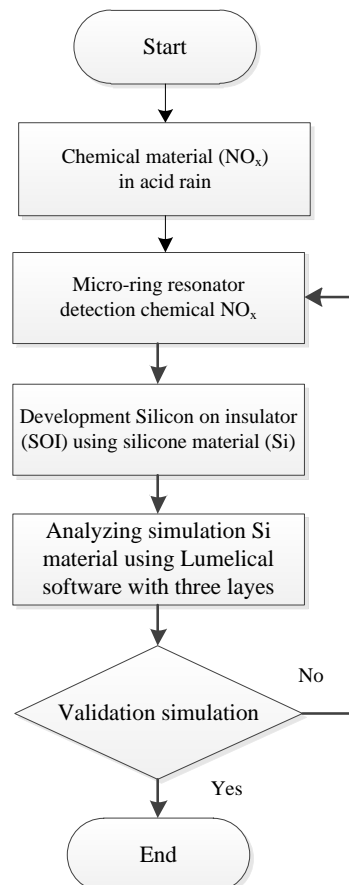
These models will analyze the optimum design parameter from LUMERICAL simulator. The simulation result is calculated base on the sweep of time drop from the variety of gap. Three models shows the difference of layer dimension at the upper layer between Figure 3(a) and 3(b), then the additional layer at the bottom part can be seen at Figure 3(c) [5, 7].



**Figure 3.** Three models of micro – ring resonator with the difference of dimension layer (a) Model 1, Ring resonator and signal waveguide are separate part, (b) Model 2, The ultimate layer connecting ring resonator and signal waveguide, and (c) Model 3, addition layer at the bottom part.

### 2.5. Micro-ring resonator for acid rain sensing application

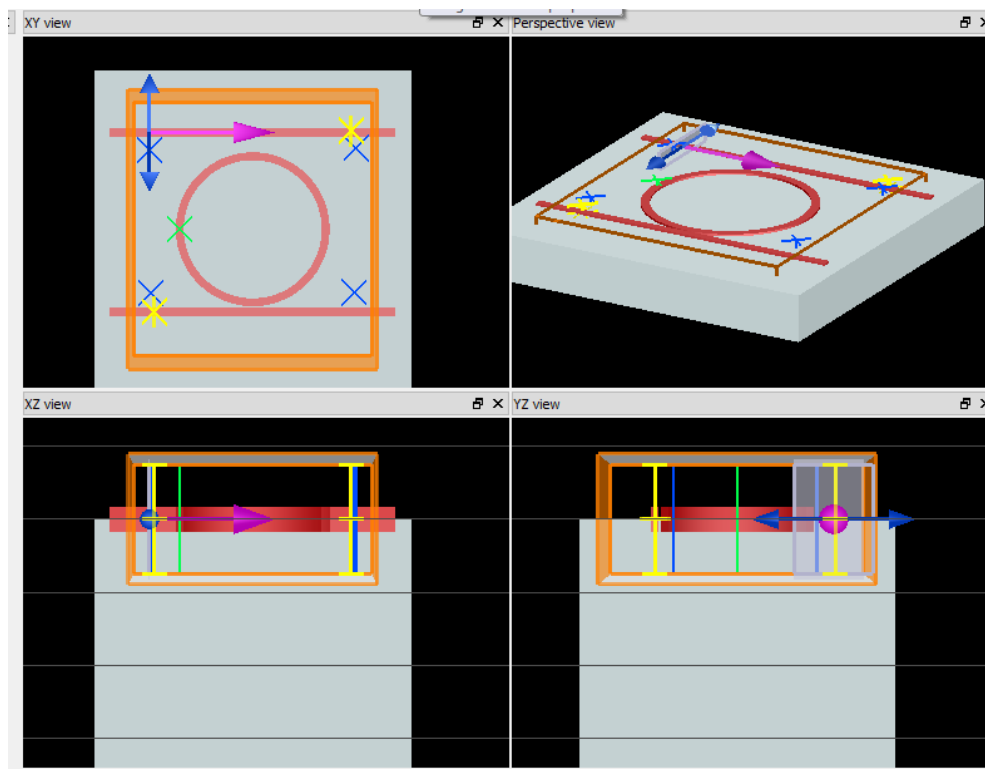
The applications of micro-ring resonator to detect acid rain were developed in this study. The combination designs of micro-ring resonator using SOI with three layers were analyzed using LUMERICAL software. Figure 4 shows flowchart of micro-ring resonator mechanism for acid rain sensing in near future.



**Figure 4.** Flowchart mechanism micro-ring resonator for acid rain sensing

Simulation of Micro Ring Resonator for sensing application was compared between the distance of sliced input and the ring resonator part. The bottom part between the ring part and the sliced output were similarly. Furthermore, the two of gap distances must be symmetrical size for getting the result of sweep time and the quality factor.

Three conditions of gap will be seen base on the model 1, 2 and 3, while simulation result will provide the optimum condition. We changed the variables referred on the actual circumstances or conditions that we expect in the measurements. Simulation result will shows the calculation using FDTD analysis, as shown in Figure 5.

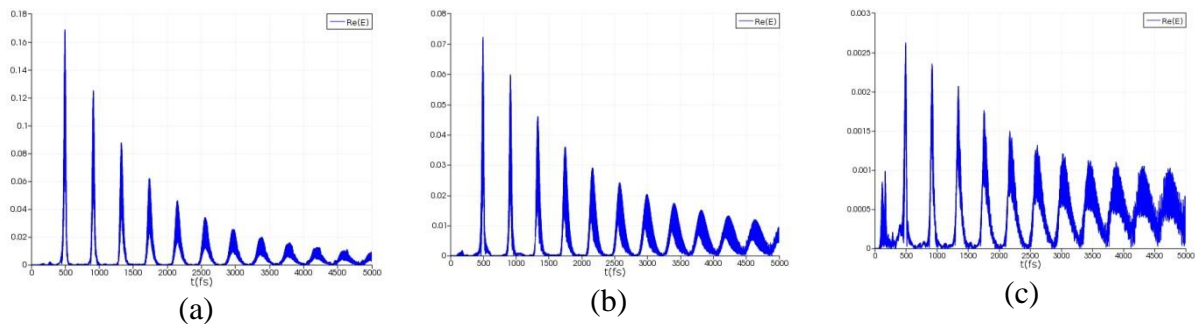


**Figure 5.** Simulation modelling setup of Micro Ring Resonator for Acid Sensor

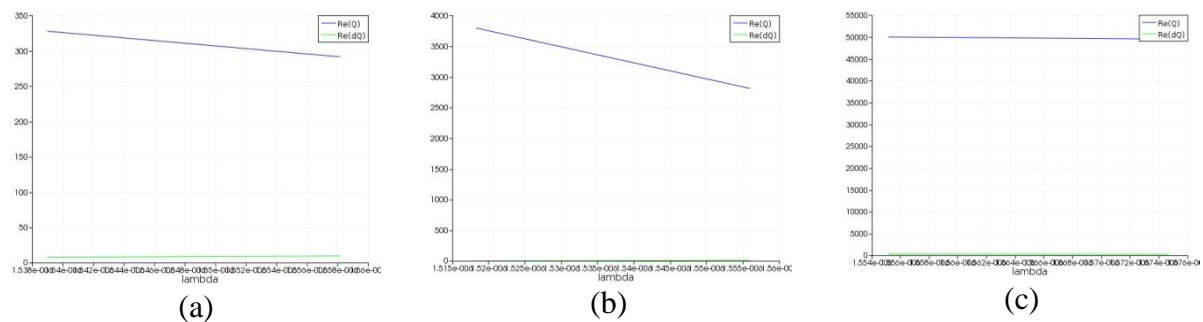
### 3. Results and Discussion

Base on  $Q$  – factor, this micro – ring resonator can determine the amplitude of the light field that refers to the sweep of time drop. It is started from 0 until 5000 second with the variation of gap 10 nm, 50 nm and 200 nm. The optimum design of model 1 that was chosen is 50 nm for gap width based on table 2. Figure 6 shows the spectrum result that was affected by background noise. Sweeping time is started from 0 second until 5000 second with increment step is 500 second. The optimum value is defined as lowest amplitude of the light field. Comparing between Figure 4 and Figure 5, it can be seen that alteration intensity of light field along the sweep of time – drop. Figure 6 gives the spectral information that higher of gap width, it will perform low amplitude of the light field and will occur the background noise effects.

Here, Figure 7 shows the quality factor ( $Q$ ) with variety of the wavelength of the light source. The range of the wavelength is determined from calculation range of FSR in order to be able to compare the quality of light source changes issued as transmitted information. In optimum condition with the gap width of 50 nm, it can be stated that great slope lines indicate good quality factor. If the condition of the quality factor is fixed throughout the wavelength range, it can be stated that the wavelength of light source is mixed with the external disturbances. This condition still not meets qualification of sensor application caused the result of quality shows below 5000.

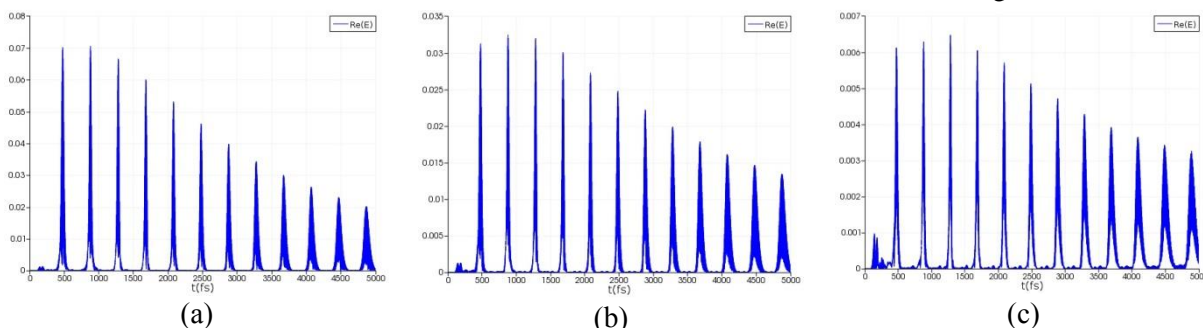


**Figure 6.** The sweep of time – drop spectral result base on gap width at model 1 for (a) gap 10 nm, (b) 50 nm and (c) 200 nm.



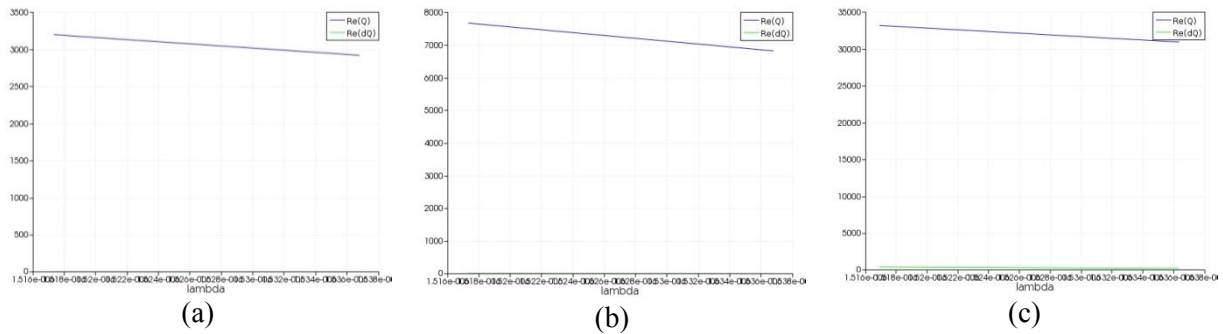
**Figure 7.** The quality factor (Q) of micro-ring resonator based on the wavelength of the light source for (a) gap 10 nm, (b) 50 nm and (c) 200 nm.

Furthermore, Figure 8 is the spectrum results of light field amplitude according the variety of gap. The variety of value is started from 80 nm to 200 nm that shown in below. These graphs are results of simulation that refers to model – 2 from ring resonator in Figure 3. The variation of simulation gives the assumption to add the ultimate layer. The additional value is given as a constant that will compared with the variety of gap width. The optimum parameter of model – 2 is gap width amounted 120 nm, it is a result simulation that sufficient with design expectation of  $Q = 7670.5$  (sufficient for sensor) and  $FSR = 20.69$  nm. Figure 9 are the graphs of the quality factors that fitted by the gap width 80 nm, 120 nm and 200 nm. This model shows different of Q where the optimum condition creates the significant value that near to the parameters of sensor application in micro-ring resonator. The optimum condition of this model can fix up the quality of the signal that is injected into the ring resonator because the external disturbances or as a sensor can affect the refractive index on the circular ring resonator area.



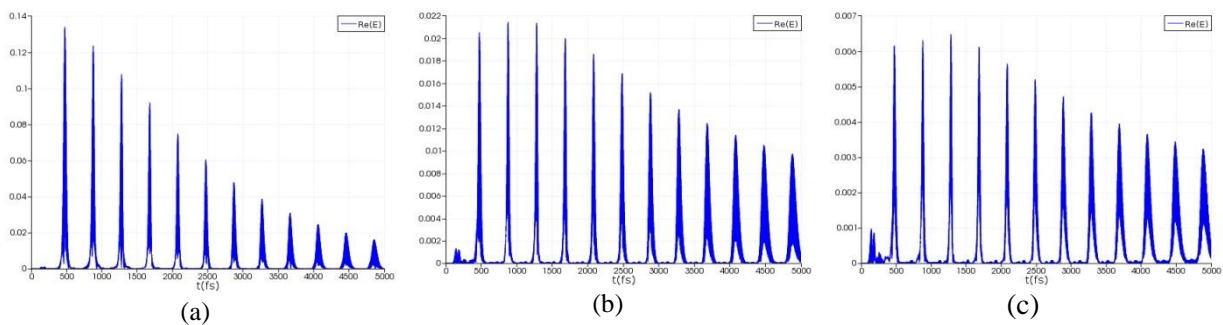
**Figure 8.** The sweep of time – drop spectral result at model 2 for (a) gap 80 nm, (b) gap 120 nm and (c) gap 200 nm





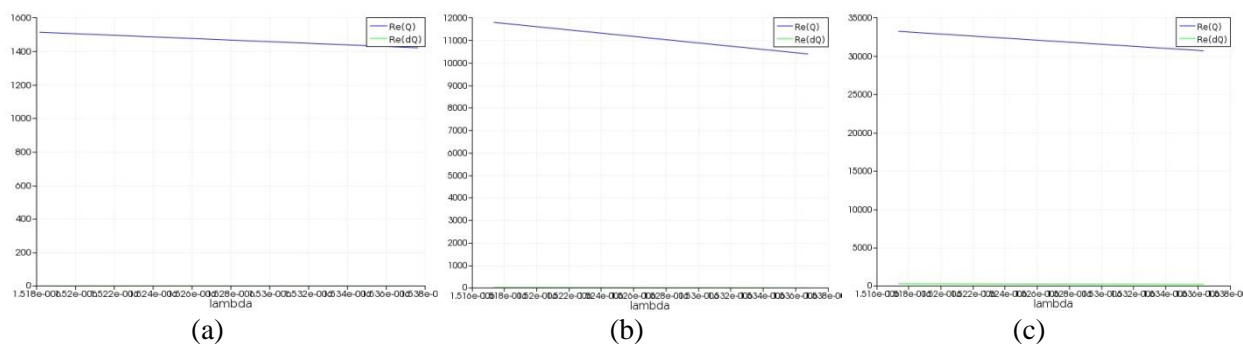
**Figure 9.** The quality factor (Q) of micro-ring resonator based on the wavelength of the light source at model 2 for (a) gap 80 nm, (b) 120 nm and (c) 200 nm.

Figure 10 are the spectrum results of light field amplitude according the variety of gap at model 3. These variations are started from 50 nm to 200 nm where a simulation result shows the assumption to add of bottom layer from ring resonator. The additional of bottom layer is given as a constant that will affect the factor quality. The optimum design parameter of gap width for model 3 is 130 nm and it is meet sufficient with design expectation of Q around 9599.85 (sufficient for sensor) and FSR = 20.74 nm.



**Figure 10.** The sweep of time – drop spectral result at model 3 for (a) gap 50 nm, (b) gap 140 nm and (c) gap 200 nm

Figure 11 are the graphs of the quality factors that fitted by the gap width 50 nm, 140 nm and 200 nm. Q factor of model 3 creates the difference of slope line and Q values. The additional effects of bottom layer from ring resonator was performed the quality factor that it is close to initial assumption.



**Figure 11.** The quality factor (Q) of micro-ring resonator based on the wavelength of the light source at model 3 for (a) gap 50 nm, (b) gap 140 nm and (c) 200 nm



#### 4. Conclusion

The development micro-ring resonator with three layers using wafer Silicon layer (Si), Silicon Oxide (SiO<sub>2</sub>) Layer and Silicon layer (Si) to detect acid rain was successful. The highest value of the width gap will provide the effect of the amplitude value and also low coefficient results. So as, the high value of the ring resonator will supply the spectral disturbance effects and present the slope line and tend to be flat along the predetermined of the FSR value. This simulation shows the real conditions base on the assumed parameter caused the optimum value is a maximum value for the FSR condition. When the FSR value gives the 0 point, it means that no occurrence of light propagation in the ring resonator and the absence of light coupling process from input bus – line to the ring resonator and vice versa.

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