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PERFORMANCE ENHANCEMENT OF OPTICAL MICRORING RESONATOR USING TAGUCHI METHOD EXPERIMENTAL DESIGN

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ABSTRACT

Taguchi method is a statistical approach to optimize the design parameters and improve the performance at a low cost. In this paper, Taguchi method is used as an attempt to analyze and optimize the Microring Resonators (MRRs) design, a multiple application device in optical communication systems. The silicon-on-insulator (SOI) wafer was selected as the medium of waveguide construction, with four control factors considered, namely width of rings and channels, radii of the microring, upper rib waveguide height and gap size. The analysis of variance (ANOVA) was adopted to analyze significant trends occurring on the Quality Factor (Q) and insertion loss (IL) performances under different sets of control factor combinations. Optimum parameter values were obtained and the confirmation experiments were also carried out. Upon optimization, the Q value improved to 1550 from 786 and IL decreased to 0.03 dB from 0.27 dB. It is verified via Taguchi analysis that not only the design constraints of the Microring Resonator can be identified, the performance of the design can be enhanced as well.

Keywords: photonic device, silicon fabrication, taguchi method, microring resonator.

INTRODUCTION

The development of silicon-based photonic devices has become one of the most important trends in the field of optical communications in recent years. A large number of devices have been developed and introduced over recent years, boosted by the growing demand for new photonic components, most of which are based on semiconductor substrate and silicon-based material from group III-V[1-3]. According to (Bogaerts et al., 2012), silicon will become the main platform for the integration of photonic devices due to its fabrication maturity and high refractive index difference4. The silicon photonics technology growths have indirectly witnessed the development of various Microring Resonator- (MRR) based devices such as optical modulator, optical filter, optical switch and multiplexer [5-7].

MRR has attracted widespread attention in the field of research because of its many advantages such as high quality factor, simple architecture and compact size.
By altering the composition of the shape, size or material, MRR can be tuned to support specified optical modes spectrum, frequency and pattern of emissions. MRR configuration can also be cascaded through various ways to build different optical components. The versatility of MRR-based devices has given it high potential as an ideal choice to be implemented in Wavelength Division Multiplexing System (WDM). MRR performance is dependent upon the waveguide physical design such as waveguide width, MRR radius and the distance between the bus waveguides and the ring waveguide. Optimizing the design parameters (or control factors, CFs) of the MRR is important in which small parameters variation can affect the overall device performance. Using a statistical method called the Taguchi method, the relationships between all the design parameters can be known and the most significant control factor can be determined with the involvement of fewer experiments as compared to 'trial and error method'. The method will aid to simplify the process of the device development where attention can be focused on the factors that have a significant impact on the performance of the device and control measures can be carried out in order to avoid changes in the design factor. By optimizing the control factors, the performance of the device can indirectly be enhanced [8-9].

Microring Resonator (MRR) design

MRR is a compact micron-sized resonator used as a basic element in most optical communication networks. MRR basic configuration is as shown in Figure-1. It consists of two straight waveguides and a microring waveguide. R is the radius of the ring, g is the gap distance between the straight waveguide and microring waveguide, W is the width of the waveguides and h is the etching depth. H is the height of silicon layer on the insulator. Silicon-on-insulator (SOI) wafers are used as a medium to form the waveguide and in this study, a silica layer (SiO_2) acts as an insulator. Straight waveguide or bus waveguide serves as the input and outlet ports, while microring acts as a wavelength selector element. In this simple configuration, there are two output ports, which are the through port and the drop port. In on-resonance condition, the input signal will couple into the microring waveguide and then exit at the drop port, while in the off-resonance condition; the input signal will bypass the microring and be guided to the through port. Figure-2 portrays the observed optical power at the through and drop ports, where the dashed line represents the through port output and the other represents the drop port output.

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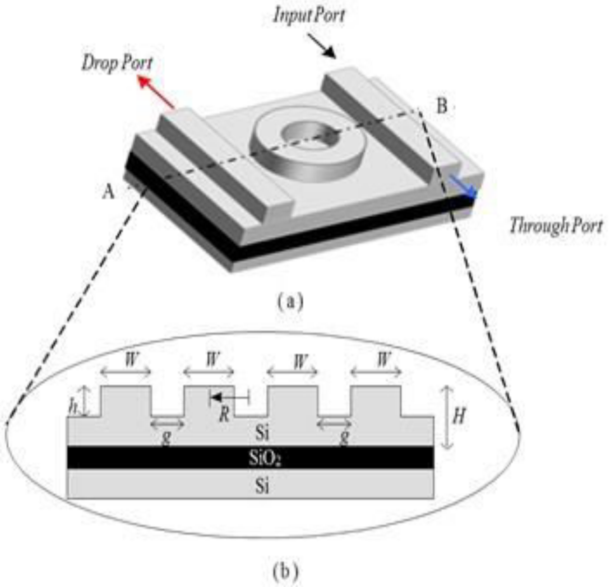

Figure-1. MRR schematic diagram (a) top view and (b) cross-sections from A to B.

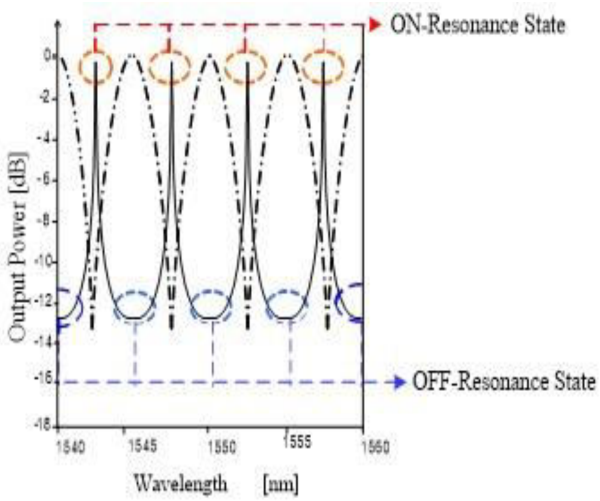

Figure-2. Example of MRR signal spectrum.

Taguchi design method

In designing high performance MRR, all of these conditions should be taken into consideration: single mode behavior, high Q, large FSR, compact size and low power consumption. In this study, the objective of the optimization is to get low IL and high Q value. Taguchi method involves the analysis that reveals the most significant control factor in achieving the goals of optimizing, which indirectly facilitates the process of finding a solution to improve the device performance. The steps involved in the optimization of the MRR filter are summarized in Figure-3.

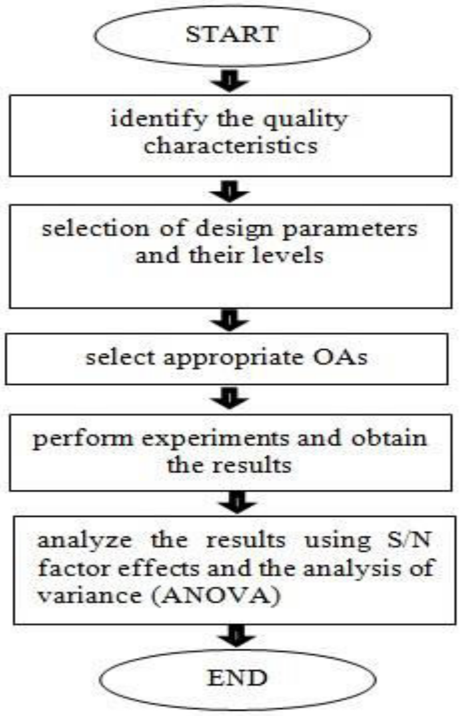

Figure-3. Process flow of the design factors optimization

The Taguchi quality characteristics studied in this research was signal-to-noise ratio (SNR) of 'the smaller the better' for the IL and 'the larger the better' for Q. For 'the smaller the better', the SNR, η can be computed by referring to Fowlkes & Creveling, 1995[10]:

$$\eta = -10\log_{10}\frac{1}{n}\sum_{i=1}^{n}\left(Y_1^2 + Y_2^2 + ...Y_n^2\right) \tag{1}$$

where n is the number of test and Y_1 toY_n is the value of IL for each experiment.

For 'the larger the better', the SNR, η can be calculated by:

$$\eta = -10\log_{10}\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{y_i^{\,2}}\right) \tag{2}$$

where n is the number of experiments and y_i is the value of Q obtained for each experiment.

Four design parameters or control factors are identified for this investigation to evaluate the influence of those parameters to the MRR performance. L^9 orthogonal array arrangement is adopted in this study as it can operate four parameters, each at three levels. The control factors (CFs) to be studied are shown in Table-1. The control factors chosen are due to the highest possibility to experience dimension variations during the real fabrication process. It is known that the fabrication process is strongly influenced by environmental factors such as pollution, working techniques and temperature. All these will indirectly contribute to imperfections of the waveguide structure. Table-2 shows the combinations layout for each CF (called an experiment in Taguchi analysis) conducted in which the overall number of experiments to be carried out is nine. The results of all the experiments are transformed into the form of signal to noise ratio, SNR. Signal in this study is defined as the desired effect on the desired output characteristics, while the noise represents unwanted effects or interference signals. The SNR values were then analyzed by analysis of variance (ANOVA) method. ANOVA was conducted to interpret the simulation data and the impact of any changes in CF. Through ANOVA analysis using Minitab software, the main effect plot will be displayed in graphical form in which the highest SNR indicates the optimum CF level.

Table-1. Control factors and their levels.

Symbol	CF	Unit	Level 1	Level 2	Level 3
R	Radius	Mm	R-0.5	R	R+0.5
g	Gap width	Nm	100	150	200
W	Waveguide Width	Nm	400	410	420
h	Etching Height	Nm	120	170	220

Table-2. Experiments Layout using OAL^9.

Exp	Design Level				SNR, η (dB)
	R	G	W	h	
1	1	1	1	1	η_1
2	1	2	2	2	η_2
3	1	3	3	3	η_3
4	2	1	2	3	η_4
5	2	2	3	1	η_5
6	2	3	1	2	η_6
7	3	1	3	2	η_7
8	3	2	1	3	η_8
9	3	3	2	1	η_9

RESULTS AND DISCUSSION

From the spectral response of a single MRR filter, SNR quality of 'the smaller the better' for IL and 'the bigger the better' for Q are calculated using Eqn. (1) and (2). The final L^9 OA displaying response values and their corresponding S/N ratio values for both IL and Q are shown in Table-3 and 4 respectively. The Minitab software was utilized to perform the statistical analysis.

It can be clearly seen that changes in MRR dimension have a significant impact on the IL. It can be observed by looking at the difference between the maximum and minimum SNR value, where huge difference indicates a significant impact on the performance of MRR as a result of changes in the geometry.

It is also noted that experiment number 1, 4 and 8 provide the highest SNR value for IL and experiment number 9 for Q. Regardless of the category of the quality characteristics, greater SNR is preferable. Highest SNR corresponds to the best combination of the CF to obtain the desired quality characteristics. From both Tables, the min value for the both quality characteristics is also calculated.

Table-3. L^9 response values and S/N ratio for IL.

Exp.	R	g	W	h	IL (dB)	SNR (dB)	Min SNR (dB)
1	1	1	1	1	0.07	23.0980	14.75
2	1	2	2	2	0.11	19.1721	
3	1	3	3	3	0.52	5.6799	
4	2	1	2	3	0.07	23.0980	
5	2	2	3	1	0.52	5.6799	
6	2	3	1	2	0.21	13.5556	
7	3	1	3	2	0.4	7.9588	
8	3	2	1	3	0.07	23.0980	
9	3	3	2	1	0.27	11.3727	

Table-4. L^9 response values and S/N ratio for Q.

Exp.	R	g	W	h	Q	SNR (dB)	Min SNR (dB)
1	1	1	1	1	523	54.3700	59.15
2	1	2	2	2	646	56.2047	
3	1	3	3	3	1045	60.3823	
4	2	1	2	3	757	57.5819	
5	2	2	3	1	870	58.7904	
6	2	3	1	2	863	58.7202	
7	3	1	3	2	1161	61.2966	
8	3	2	1	3	1335	62.5096	
9	3	3	2	1	1336	62.5161	

Since the analysis is based on orthogonal experimental design, the SNR for each CF at different levels can be identified. SNR represented by each CF is as shown in Table-5 for IL and Table-6 for Q. Δ is the difference between the maximum and the minimum SNR. In analyzing the SNR, the dominant CF or the CF that grants the most impact on the optimization target is determined by comparing the value of Δ for every CF. High Δ value reflects great influence on the target performance, whereas small Δ testifies minimal impact on CF changes.

For example, from Table-5, the width of the waveguide structure was observed as the most significant CF, followed by the gap width, etching depth and ring radius for the optimization of IL value. On the contrary, in optimizing the value of Q, the most dominant CF was MRR ring radius, followed by the gap width, waveguide width and the etching depth consecutively as shown in Table-6. For SOI structure with a high refractive index difference (HIC), it is expected that the etching depth will give minimal impact as the dimension of the MRR varies. This is due to the shape of the rib waveguide chosen, providing low sensitivity to height and depth changes and is able to concentrate the optical signal at the center of the waveguide rib with minimal loss (Png et al., 2004).

Table-5. SNR response for IL.

CF	SNR			
	Level 1	Level 2	Level 3	Δ
Radius, R	15.983	14.111	14.143	1.872
Gap Width, g	18.052	15.983	10.203	7.849
Waveguide Width, W	19.917	17.881	6.440	13.478
Etching Depth, h	13.304	13.562	17.292	3.908

Table-6. SNR response for Q.

CF	SNR			
	Level 1	Level 2	Level 3	Δ
Radius, R	56.99	58.36	62.11	5.12
Gap Width, g	57.75	59.17	60.54	2.79
Waveguide Width, W	58.53	58.77	60.16	1.62
Etching Depth, h	58.56	58.74	60.16	1.60

The main effect plot for the IL and Q optimization is shown in Figure-4 and 5. The straight line in the middle of the graph shows the mean value of SNR, while the combination of CF that provides optimum value for each quality characteristics can be determined by referring to the highest level of SNR for each CF. Based on Figure-4, the best parametric combination for IL optimization is R = 5.5 µm, g = 100 nm, W = 400 nm and h = 220 nm. Moreover, the best parametric combination for optimizing the Q value is R = 6.5 µm, g = 200 nm, W = 420 nm and h = 220 nm as depicted in Figure-5. Table-7 summarizes the optimized design parameters setting for both the IL and Q.

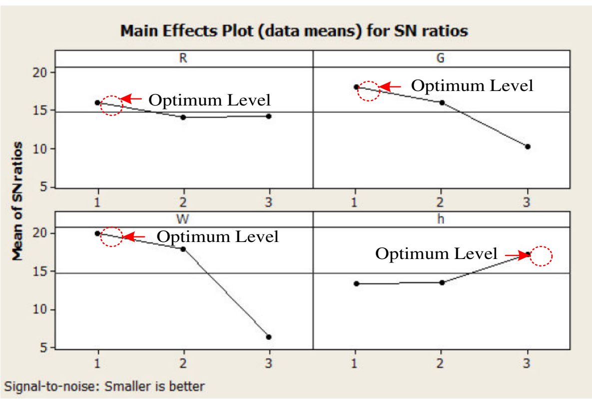

Figure-4. S/N response for IL.

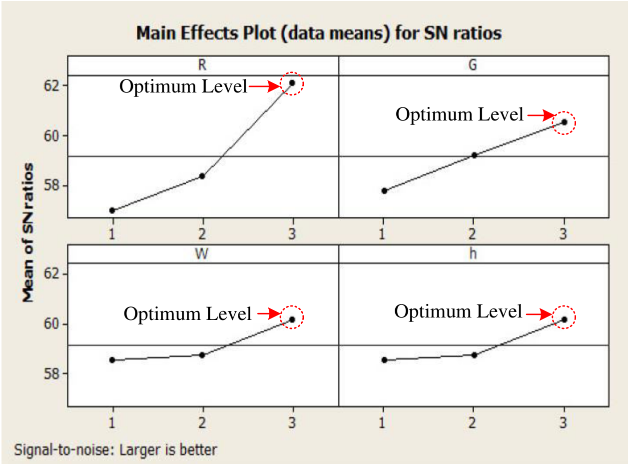

Figure-5. S/N response for Q.

Table-7. Best setting for IL and Q optimization.

Optimization Target	Control Factor			
	Radius (µm)	Gap Width (nm)	Waveguide Width (nm)	Etching Depth (nm)
IL	5.5	100	400	220
Q	6.5	200	420	220

Once the best setting for optimal level has been specified, the improvement of the quality characteristics was predicted and verified via confirmation test. Both prediction and verification was done by employing the Minitab software and the results are shown in Table-6. It can be seen that, before optimization, the MRR experiences 0.27 dB IL with the Q value of 786. The predicted IL based on the best setting is 0.00 dB with the Q value of 1584. Upon confirmation test, it was observed that the IL improved 89 % from the initial expected result, while the Q was enhanced by 764. For both quality characteristics, good agreement between the predicted and the actual value was observed.

Table-8. Result of the confirmation test.

Quality Characteristics	Level	Value	Result	
			IL (dB)	QF
IL	R_1, g_1, W_1, h_3	Before Optimization	0.27	-
		Predicted Result	0.00	-
		Confirmation Test Result	0.03	-
Q	R_3, g_3, W_3, h_3	Before Optimization	-	786
		Predicted Result	-	1584
		Confirmation Test Result	-	1550

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CONCLUSIONS

It is verified that the performance of the MRR-based devices are dependent on the selection of the design parameters, particularly the waveguide structure, i.e. gap distance, radius and so on. Therefore, the study of the effects of waveguide geometry variations is crucial in the design of MRR-based devices. Investigation on design parameters optimization using Taguchi statistical method in this study provides an overview of the design constraints. Therefore, extra precautions can be taken during the actual fabrication process. Upon optimization, the best dimension for MRR design was R= 5.5 µm, g = 100 nm, W= 400 nm and H= 220 for IL improvement and R= 6.5 µm, g = 200 nm, W= 420 nm and H= 220 nm for Q improvement.

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