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On the effectiveness of Taguchi method in optimizing the performance of parallel cascaded MRR array (PCMRRA)

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This paper attempts on optimizing the quality of Microring Resonator (MRR) based optical filter under various design parameters setting by using the Taguchi method in order to enhance the performance of the developed device. By using the Taguchi Method, tolerance analysis was carried out to investigate the effects of the device dimension changes on the overall performance. The orthogonal array, signal to noise ratio (S/N) and analysis of variance were employed to find the best parametric combination of design parameters setting, where the quality characteristics of interest are the quality factor and insertion loss, which are both important parameters in optical filter design. The results showed that the optimal combination of design parameters for insertion loss optimization are ring radii of 5.5 µm, gap separation distance of 100 nm, waveguide width of 400 nm and etching depth of 220 nm. Meanwhile, the optimal parametric design settings to optimize the Q-factor value are ring radii of 6.5 µm, gap separation distance of 120 nm, waveguide width of 420 nm and etching depth of 120 nm. Optimum results between both values are finally verified with the aid of confirmation experiments carried out using the Fullwave software. It was found that design tradeoffs between both values occur when the ring radii are 6.5 µm, gap separation distance is 100 nm, waveguide width is 400 nm and etching depth is 220 nm.

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Keywords: Microring Resonator, Robust Design, Silicon Photonic, Taguchi Method

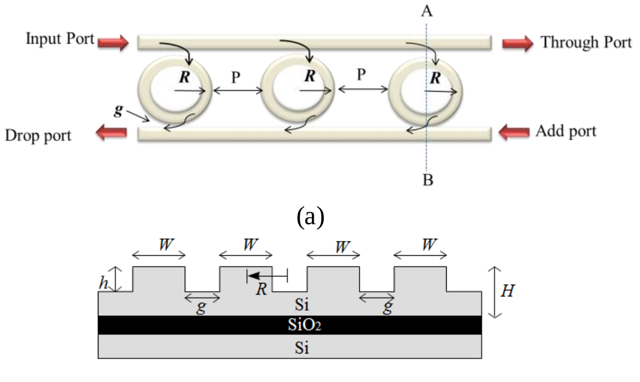
1. Introduction

Optical filters are very crucial devices for optical communication networks mainly in Dense Wavelength Division Multiplexing (DWDM). Recently, a lot of works have been performed in the development of optical filters, such as plane grating, Fabry Perot interferometer, Mach-Zehnder interferometer and microring resonator (MRR) [1-5]. Among all, MRR has the potential in photonic integrated circuits (PIC) due to its ultra-small size, flexibility simple construction and easy integration with current CMOS fabrication process [6-7].

The basic construction of the MRR optical filter consists of one straight waveguide and one circular waveguide or often called as the microring waveguide. The performance of a single MRR filter can be enhanced by altering the Lorentzian spectral response of a single MRR, realizing by cascading the MRR in parallel, named the Parallel Cascaded MRR Array (PCMRRA). The aim of this paper is to explore the feasibility of employing the statistically approach of the Taguchi method in developing a high performance MRR filter by optimizing the design parameters, which includes ring radii (*R*), gap size between the straight waveguide and the ring waveguide (*g*), waveguide width (*W*) and etching depth (h). The design parameters or the so-called control factors (CFs) are parameters that could potentially change during the fabrication process. This process is heavily influenced by environmental factors, such as contamination, working techniques, and temperature, which eventually indirectly contributes to structural imperfections of the waveguide. By applying the Taguchi Method, control factor, which contributes to the most impact on the device performance will be determined. Therefore, despite improving the overall MRR performance, results from the statistical analysis can be employed as a reference where special precaution can be taken during the fabrication process in order to minimize the fabrication error. The requirements of MRR filter design should consider the state of single-mode, high-quality factor (Q), large Free Spectral Range (FSR), low insertion loss, compact size and low power consumption [6-7]. In this study, the objective of the optimization is to get low insertion loss (IL) and high Q due to that the performance of the filter in the circuit Wavelength Multiplexer (WDM) is inextricably linked with the IL and Q.

2. Parallel Cascaded MRR Array (PCMRRA)

The schematic diagram of the PCMRRA is depicted in Fig. 1(a), while the cross-section view from A-B is shown in Fig. 1(b). The key dimensions of PCMRRA include the ring radii (*R*), the distance between the straight waveguide and the microring waveguides (*g*), the arm length between adjacent microrings (*P*), the waveguide width (*W*), the etch depth (*h*) and the waveguide height measured from the upper SiO$_2$ layer to the top of the silicon layer (*H*). Silicon-on-insulator (SOI) that was chosen with the background index is 1, the refractive index of the silicon is 3.45 and the refractive index of SiO$_2$ is 1.5, working around 1550nm region. From Fig. 1(a), the design consists of three microring waveguides and two straights waveguides. The straight waveguide will functioned as the input and output port. The waveguide dimensions are fixed to R = 6 μm, g = 100 nm, h = 170 nm, P = 6.4 μm and H = 340 nm. The signal from input port will be coupled into the three microrings if the roundtrip delay is an integral multiple of 2π and was sent to the drop port. If not, the signal will bypass the microring and exit at the through port.



(a)

(b)

Fig. 1(a). The schematic diagram of the proposed design (b) the cross-section view from A-B

3. Taguchi method

One of the main problems in traditional experimental design is the difficulty in designing experiments to compare the effects and interactions of multiple variables or control factors. Some methods require a large number of individual experiments. By making use of the orthogonal array distribution, the Taguchi Method produces smaller and less costly experiments, with high reliability. The Taguchi method reveals the most significant factor control in achieving the goal of optimizing, in which indirectly facilitates the process of finding solutions to improve the performance of the device [10-12]. The steps in MRR filter design optimization are summarized as in Fig. 2.

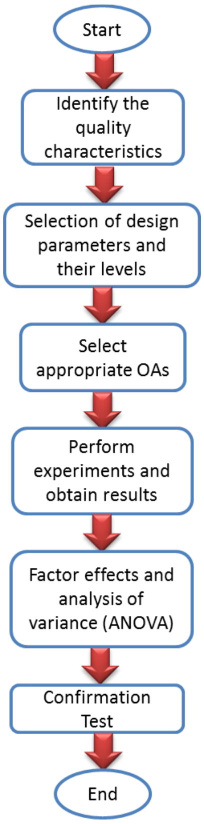


Fig. 2. Design parameters optimization process flow

The results of the design optimization were evaluated in terms of signal to noise ratio, SNR. The Taguchi quality characteristics studied was signal-to-noise ratio (SNR) of 'smaller the better' for IL and 'larger the better' for Q. For 'smaller the better', the SNR, η can be computed as:

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

where n is the number of experiment and Y_1 toY_n is the value of IL for each experiment. For 'larger the better', the SNR, η can be calculated by:

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

where n is the number of experiments and y_i is the value of Q obtained for each experiment. Selection of design parameters or control factors (CFs) and their levels are made due to the parameters that have a major influence on the MRR performance. Table 1 indicates the control factors and their levels. As deduced from Table 1, there were four control factors, each at three levels. Based on the number of control factors and their levels, the suitable orthogonal arrays (OAs) were selected as L$_9$.

Table 1. The control factors and their levels

Symbol	CF	Unit	Level 1	Level 2	Level 3
R	Radius	µm	5.5	6	6.5
g	Gap Width	nm	100	150	200
W	Waveguide Width	nm	400	410	420
h	Eching Height	nm	120	170	220

A standard Taguchi L^9 Orthogonal Array (OA) is chosen for this study, as presented in Table 2, in which the overall number of experiments carried out was nine. Minitab software was employed in this study to perform the SNR analysis, where the main effect plot will be displayed in a graphical form, showing the highest SNR that indicates the optimum CF level.

Table 2. Experiments Layout using OA L^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

Analysis of variance (ANOVA) was then applied to quantitatively estimate the relative contribution, revealing the impact of each controlled factor to the overall measured response. The basic idea of ANOVA is that the total sum of squares of the standard deviation is equal to the sum of squares of the standard deviation caused by each parameter [13-14].

ANOVA was conducted to obtain the relative contribution, ρ_F of each CF on the target output. ANOVA table is constructed using the following formulae:

$$SST = \sum_{i=1}^{n}\left(\eta_i - m\right)^2 \quad (3)$$

$$SSF_{(x)} = t\left[\sum_{j=1}^{t}\left(m_{xj} - m\right)^2\right] \quad (4)$$

$$\rho_F = \frac{SSF}{SST}x100 \quad (5)$$

The ratio between the sum of squares for each experiment, *SST* and the sum of each factor, *SSF (x)* were calculated in predicting the ρ_F. *m* represents the average value of SNR for the entire experiment, *n* is the number of experiments, ηi is the SNR for each experiment and *t* is the number of trials for each CF. m_{xj} represents the SNR for the calculated CF.

4. Results and discussion

From the transmission response of a PCMRR filter, SNR quality of 'the smaller the better' for IL and 'the bigger the better' for Q are calculated using Eqn. (1) and (2).

A. SNR analysis

As seen in Table 3 and Table 4, changes are purposefully made to the input variables (control factors) to investigate the impact of the design parameters variation on IL and Q. In these tables, the raw results of L^9 OA response values and their corresponding SNR ratio for both IL and Q were shown. Larger SNR indicates a greater impact on the device performance, where from Table 3, experiment 1 exhibits the highest SNR and experiment 9 has the most impact on Q. Hence, it can be interpreted as; although the parametric combination of experiment 9 produces excellent Q, it may contribute to a higher IL and vice versa.

Table 3. IL and S/N ratio values for experiments

Ex.	*R*	*g*	*W*	*h*	IL (dB)	SNR (dB)	Min SNR (dB)
1	1	1	1	1	1.86	-5.39026	-6.566
2	1	2	2	2	1.90	-5.57507	
3	1	3	3	3	2.30	-7.23456	
4	2	1	2	3	1.86	-5.39026	
5	2	2	3	1	2.32	-7.30976	
6	2	3	1	2	2.26	-7.08217	
7	3	1	3	2	2.19	-6.80888	
8	3	2	1	3	1.88	-5.48316	
9	3	3	2	1	2.76	-8.81818	

Table 4. Q and S/N ratio values for experiments

Ex.	*R*	*g*	*W*	*h*	Q	SNR (dB)	Min SNR (dB)
1	1	1	1	1	572	55.1479	57.8410
2	1	2	2	2	635	56.0555	
3	1	3	3	3	734	57.3139	
4	2	1	2	3	688	56.7518	
5	2	2	3	1	847	58.5577	
6	2	3	1	2	839	58.4752	
7	3	1	3	2	834	58.4233	
8	3	2	1	3	949	59.5453	
9	3	3	2	1	1035	60.2988	

The adoption of OAs experimental design in Taguchi, enables SNR for each CF at different levels to be identified, as indicated in Table 5 for IL and Table 6 for Q. Orthogonality signifies that the control factors can be explored independently of one another; where the effect of one factor does not influence the estimation of another factor. Δ denotes the deviation 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 a great influence on the target performance, whereas small Δ testifies minimal impact on the CF changes.

The analysis of SNR is shown in Table 5 and Table 6. From Table 5, it clearly indicates that the gap width is the most important parameter influencing IL, followed by etching depth, waveguide width and ring radii. In contrast, Table 6 shows that the MRR ring radius has the most significant impact on Q.

Table 5. SNR values for IL by factor level

	SNR			
CF	Level 1	Level 2	Level 3	Δ
Radius, *R*	-6.067	-6.594	-7.037	0.97
Gap Width, *g*	-6.594	-6.123	-6.595	1.849
Waveguide Width, *W*	-7.037	-7.712	-7.118	1.133
Etching Depth, *h*	-7.173	-6.489	-6.036	1.137

Table 6. SNR values for Q by factor level

	SNR			
CF	Level 1	Level 2	Level 3	Δ
Radius, *R*	56.17	57.93	59.42	3.25
Gap Width, *g*	56.77	58.05	58.70	1.92
Waveguide Width, *W*	57.72	57.70	58.10	0.40
Etching Depth, *h*	58.00	57.65	57.87	0.35

Fig. 3 and Fig. 4 portray the main effect plot for design parameters effect at each level where the target is IL and Q, respectively. The levels having the major contribution denotes by the highest SNR for each parameter were selected from the plot. From Fig. 3, by referring to Table 1, the best parametric combination for IL optimization is R_1 = 5.5 µm, g_1 = 100 nm, W_1 = 400 nm and h_3 = 220 nm. Meanwhile, as depicted in Fig. 4, the best parametric setting for Q is R_3, g_3, W_3 and h_1, which corresponds to a gap ring radius of 6.5 µm, a gap size of 200 nm, a waveguide width of 420 nm and an etching depth of 120 nm.

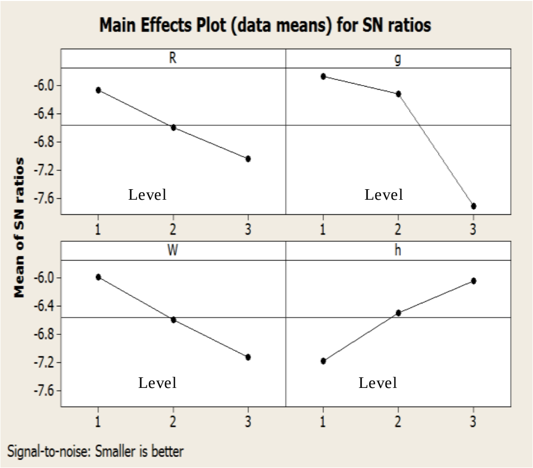


Fig. 3. Main effects plot for design parameters SNR values (IL)

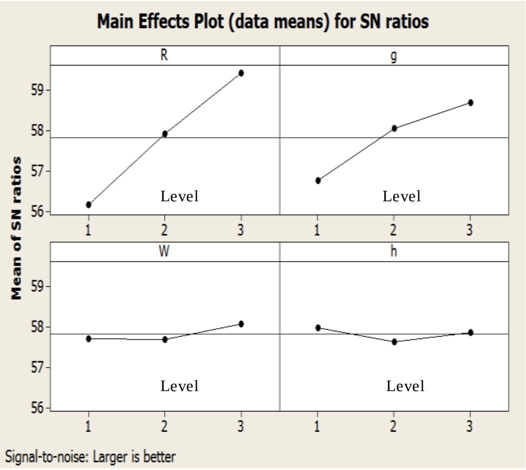


Fig. 4. Main effects plot for design parameters SNR values (Q)

B. ANOVA

Table 7 gives the contribution of each control factor to IL and Q represented by the percentage of ρ_F. It can be concluded that in order to optimize the IL value, the gap size gives the most significant effect on IL and to optimize the Q value, the ring radius has the greatest impact on Q. It can be concluded that the design trade-offs are required in order to optimize both IL and Q value. Therefore, by comparing the percentage of ρ_F for both optimization targets, the highest ρ_F for each CF was selected. Therefore, the optimal parametric combination to optimize both targets is R_3, g_1, W_1 and h_3, which corresponds to a gap ring radius of 6.5 µm, a gap size of 210 nm, a waveguide width of 400 nm and an etching depth of 220 nm.

Table 7. ANOVA table for responded raw data

Optimization Target		Parameter/Value			
IL	*Level*	R_1	g_1	W_1	h_3
	SSF(x)	1.42	6.01	1.93	1.97
	SST	11.32			
	ρ_F*(%)*	12.51	53.10	17.03	17.36
Q	*Level*	R_3	g_3	W_3	h_1
	SSF(x)	15.88	5.74	0.30	0.19
	SST	22.11			
	ρ_F*(%)*	71.83	25.97	1.35	0.85
IL and Q	*Level*	R_3	g_1	W_1	h_3

5. Confirmation test

Once the optimal combination of control factors and their levels were obtained, the final step was to verify the estimated result against the experimental value. The optimal combination of control factors setup was employed in designing the PCMRRA filter and the result was observed and concluded as in Table 8. It denotes that by optimizing the design for both IL and Q, the IL was successfully improved by 0.37 dB, while the Q value increased by more than 27%. The results show that the Taguchi technique can be a reliable tool to optimize and estimate the performance of any optical devices.

Table 8. Confirmation test result

	IL	Q
Before Optimization	2.48	578
Confirmation test	2.11	799

6. Conclusion

This study proposes a Taguchi-method to study the impact of design parameters variation on IL and Q performance of the PCMRRA. It can be concluded that, if the target performance is IL, the gap distance between the straight waveguide and the microring has the most impact to the device performance. Whereas, the size of the ring radii has to be carefully selected if the target performance is Q factor value. Upon optimizing both values, the optimal parametric combinations obtained were R_3, g_1, W_1 and h_3.

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