Robust modeling of SOI-based optical phase modulator using free carrier dispersion effect

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This paper reports the effect and optimization of design parameters of a silicon-on-insulator (SOI) optical waveguide phase modulator using Taguchi method. The modulator employing the p-i-n diode structure will be working based on free carrier dispersion effect at 1.55μm optical telecommunication wavelength. The optimization is focus to minimize the tradeoff between refractive index change and absorption loss in the device's performance. Four design parameters were explored, namely applied voltage, doping concentration, doping position and waveguide rib area. In addition, four noise factors were also included to achieve robustness of the proposed device design which is the annealing temperatures for both the p-doped and n-doped wells as well as the phosphorous and boron implant energy for both the p-doped and n-doped wells. The level of importance of the design parameters on the refractive index change and absorption loss were determined using Analysis of Variance (ANOVA). The optimum process parameter combination was obtained using the analysis of Signal-to-Noise (S/N) ratio. It was discovered that the applied voltage is the most dominant factor in determining the response of the modulator. The results show that the refractive index change and absorption loss upon Taguchi optimization is 0.00155 and 19.9dB/cm respectively.

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1. Introduction

The growing demand of active devices for tuning applications in silicon-based Photonic Integrated Circuits (PIC) provides high attraction for high-speed optical phase modulation. By changing the refractive index of the modulator, the phase of light can be controlled [1-2]. Future silicon PICs requires high speed, strong response and large modulation from the optical modulator. There are a few methods to achieve the phase modulation in silicon optical device such as by free carrier dispersion effect and thermo-optic effect. In order to provide good phase modulation, the free carrier dispersion effect is always preferred [3]. Even though, the thermo-optic optic effect is the simplest method, it suffers from high power consumption. The free carrier dispersion effect normally can be obtained through either carrier injection or carrier depletion of a p-i-n diode structure [4].

Usage of silicon-on-insulator (SOI) substrates poises to become the technology of choice for silicon-based waveguide modulators in order to get better confinement of light. This is due to the high index contrast between the silicon core and the silica cladding of the device. In addition, SOI has significant advantages in which it has very low bending loss [5-6]. Therefore, more compact device can be realized with the utilization of SOI as the substrate material [7].

It is challenging to design a silicon-based waveguide phase modulator with high performance. In order to be useful in telecommunication systems, the modulator should exhibit large modulation and low free carrier absorption loss. Unfortunately, silicon-based modulators with p-i-n structures typically have high refractive index change but suffer from high free carrier absorption loss. Therefore, in seeking a balanced response between the high refractive index change and low free carrier absorption loss, a design trade off between the two is needed in order to produce a modulator with an optimized performance. A schematic diagram of the SOI-based optical phase modulator is shown in Fig. 1.

In this paper, we demonstrate a statistical approach to optimize the desired design of a SOI-based waveguide phase modulator. The modulator was designed with the optimal balancing response between the refractive index change and the free carrier absorption loss using Taguchi Method. The orthogonal array (OA) methodology utilized in this method provides an organized set of experiments in which it allows us to identify and investigate the process parameters of the output responses [9]. Finally, the desired robust design with the optimal setting of process parameter will be achieved. The target of the robust design is to identify the process parameter that gives consistent and less variation in the output.

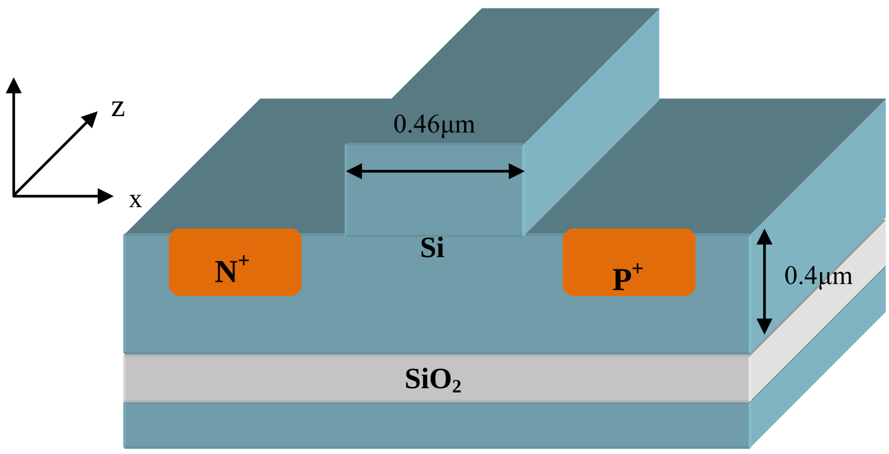

Fig. 1. Schematic Diagram of SOI Optical Waveguide Phase Modulator.

2. Theory

The free carrier dispersion effect is used in the modulation because silicon exhibits low electro-optic effect. A change in the refractive index and free carrier absorption loss of the silicon waveguide phase modulator with p-i-n diode structure can be achieved by means of free electrons and holes into the intrinsic region using forward bias. The following equation expresses the calculation of refractive index change and free carrier absorption loss at 1.55 µm wavelength due to free carrier injection of the device [11]:

$$\Delta n = -\left(8\times10^{-22}\Delta N_e + 8.5\times10^{-18}(\Delta N_h)^{0.8}\right) \qquad (1)$$

$$\Delta\alpha = 8.5\times10^{-18}\Delta N_e + 6\times10^{-18}\Delta N_h \qquad (2)$$

where ΔN_e is the change of the free electrons concentration and ΔN_h is the change of the free hole concentration.

3. Methodology

In this paper we have combined the usage of numerical modeling and Taguchi method to obtain the optimized performances of the SOI waveguide phase modulator with design tradeoff between the refractive index change and the absorption loss of the device.

3. 1 Numerical modeling

Standard silicon microelectronics fabrication processes were used to model the device using the 2D ATHENA module from SILVACO software. The modeling of the optical modulator was performed using a commercial numerical simulator SILVACO which utilizes a drift-diffusion approach [10]. The Poisson, carrier continuity and current density equations are solved numerically in two dimensions subject to the device's geometry and boundary conditions imposed by the device's contacts and biasing conditions.

The fabrication processes begin with the formation of the SOI layer. Then, the silicon layer is lightly doped with a background concentration of 1 × 10^{14} cm^{-3}. The rib waveguide is formed using the dry etching process where an oxide layer is used as a mask. The rib height and width for the waveguide structure is chosen in order to have single mode behaviour.

The active area of the p-i-n diode structure was fabricated through the ion implantation process where both the p^+ and n^+ region were implanted with boron and phosphorus respectively. The p^+ type region was doped with boron concentration of 5 × $10^{18}cm^{-3}$ at ion implantation energy of 10 keV and annealing temperature of 600˚C. While the n^+ type region was doped with phosphorous concentration of 5 × $10^{18}cm^{-3}$ at ion implantation energy of 30 keV and annealing temperature of 600˚C. Finally, the metallization process was done to form the electrodes of anode and cathode.

The characterization of the completed design structure of the SOI optical phase modulator device was simulated in ATLAS to provide values of free carrier concentration in the optical guiding region at optical wavelength of 1.55µm. In this paper, dc electrical simulations have been performed to the active region of the phase modulator. The device is operated by applying an external electrical signal to the electrodes [13]. By observing the doping concentrations variations at the waveguide centre (x=2), it enables us to work out the refractive index change for a specific forward bias voltage.

3.2 Taguchi orthogonal L_9 array method

Taguchi method was used to find the optimization responses of optical phase modulator by using orthogonal array methodology. The orthogonal array allows for significant reduction in the number of experimental runs to find the optimal solution. Fig. 2 shows the basic step of optimization by using Taguchi Method. Basically, this method is able to obtain the best process parameters setting to optimize and improve the refractive index change (Δn) and free carrier absorption loss (Δα) of the device. Four control factors were modified and examined which are the applied voltage, doping position, doping concentration and waveguide rib area. Four noise factors which are annealing process temperature for N doping, phosphorous implant energy for N doping, annealing process temperature for P doping and phosphorous implant energy for P doping were also selected. The values of the control factors and noise factors at different levels are listed in Table 1 and Table 2 respectively. In this study, every control factor has three different levels. Therefore L_9 (3^4) orthogonal array was used and 9 experiments with different setting of control factors have been done [14]. The experimental layout of the L_9 orthogonal array is shown in Table 3.

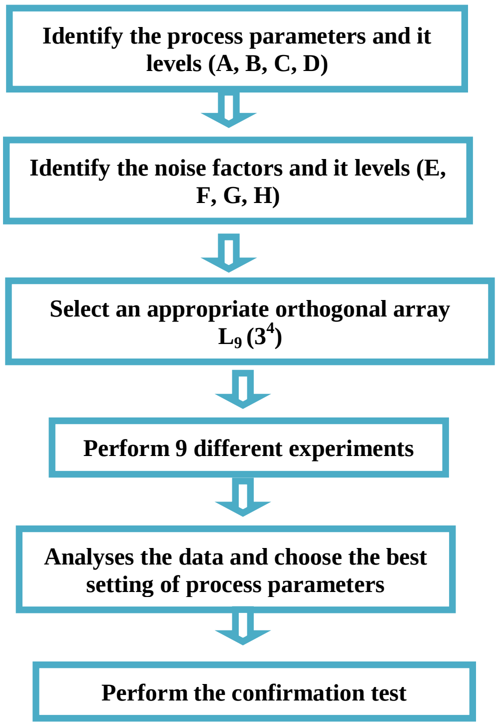

Fig. 2. Basic step of Taguchi Method for optimization of Optical phase modulator.

Table 1. Process parameters and their levels.

Symbol	*Process Parameter*	*Unit*	*Level 1*	*Level2*	*Level3*
A	*Applied Voltage*	*V*	*1.0*	*0.9*	*0.8*
B	*Doping Concentration*	cm^{-3}	*5e18*	*5e19*	*5e20*
C	*Doping Position*	*µm*	*0*	*0.25*	*0.5*
D	*Waveguide Rib Area*	nm^2	*500x580*	*400x460*	*300x340*

Table 2. Noise factors and their levels.

Symbol	*Noise Factors*	*Unit*	*Level 1*	*Level2*
E	*Annealing Process Temperature for N Doping*	*˚C*	*600*	*610*
F	*Phosphorous Implant Energy for N Doping*	*keV*	*30*	*40*
G	*Annealing Process Temperature for P Doping*	*˚C*	*600*	*610*
H	*Boron Implant Energy for P Doping*	*keV*	*10*	*20*

Table 3. Experimental layout using L9 (3^4) Orthogonal Array.

No. of Experiment	A Applied Voltage	B Doping Concentration	C Doping Position	D Waveguide Rib Area
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

4. Results and discussions

4.1 Primary experiment

The characterization of initial design of the optical phase modulator was conducted before optimization process by Taguchi Method. The free holes and electron concentration at the intrinsic region of the waveguide were observed and measured. Both the refractive index change and free carrier absorption loss were calculated using equation (1) and (2) respectively. The refractive index change of 0.00518 and free carrier absorption of 81.43 dB/cm was obtained at 1.0V applied voltage. These design settings were processed with Taguchi Method in order to get the desired robust design.

4.2 Optimization using Taguchi Method

In this section, only 9 experiments with selected combination of control and noise factors by the orthogonal array methodology were performed. The experimental results of 9 set of experiments for refractive index change and free carrier absorption loss of the phase modulator are shown in Table 4 and Table 5 respectively.

i. Analysis of SNR (Signal to Noise Ratio)

In Taguchi method, the SNR is recommended to measure the quality characteristics. The term 'signal' represents the desirable value (mean) meanwhile the term 'noise' represents the undesirable value (standard deviation) for the output characteristic. Therefore, SNR is the ratio of the desirable value to the undesirable value and it is used to measure the quality characteristic deviating from the desired value. The SNR is defined as;

$$\eta = -10\log(M.S.D) \tag{3}$$

where M.S.D is mean-square deviation for output quality characteristic.

In order to develop good modulation efficiency of the modulator, we need high refractive index change. Therefore, the refractive index change is categorized under Taguchi's SNR of 'larger-the-better' quality characteristics. In contrast, the modulator will perform badly with high losses inclusive of free carrier absorption loss. In this case study, the free absorption loss characteristics belongs to SNR of 'smaller-the-better' quality characteristics.

Table 4. Refractive Index Change (Δn) values for optical phase modulator.

Exp. No	Refractive Index Change (Δn)							
	Δn #1	Δn #2	Δn #3	Δn #4	Δn #5	Δn #6	Δn #7	Δn #8
1	6.67e-03	7.52e-03	7.23e-03	6.94e-03	6.82e-03	7.15e-03	6.98e-03	7.30e-03
2	1.48e-03	1.64e-03	1.53e-03	1.61e-03	1.54e-03	1.54e-03	1.58e-03	1.53e-03
3	3.25e-04	3.21e-04	3.21e-04	3.26-e04	3.23e-04	3.20e-04	3.23e-04	3.20e-04
4	4.32e-03	4.22e-03	4.22e-03	5.07e-03	5.20e-03	4.31e-03	5.15e-03	4.20e-03
5	1.61e-03	1.62e-03	1.62e-03	1.69e-03	1.68e-03	1.61e-03	1.69e-03	1.62e-03
6	3.23e-04	3.19e-04	3.19e-04	3.25e-04	3.28e-04	3.23e-04	3.24e-04	3.20e-04
7	6.00e-03	6.30e-03	6.30e-03	6.28e-03	5.75e-03	6.06e-03	6.28e-03	6.27e-03
8	7.15e-04	9.30e-04	9.30e-04	1.25e-03	7.11e-04	1.07e-03	1.24e-03	1.25e-03
9	3.34e-04	3.32e-04	3.37e-04	3.37e-04	3.36e-04	3.35e-04	3.37e-04	3.33e-04

Table 5. Absorption Loss (Δα) values for optical phase modulator.

Exp. No	Absorption Loss (Δα) dB/cm							
	Δα #1	Δα #2	Δα #3	Δα #4	Δα #5	Δα #6	Δα #7	Δα #8
1	109.09	125.25	119.61	114.23	111.89	118.25	115.02	121.00
2	18.96	21.27	19.67	19.76	19.85	19.85	20.41	19.58
3	3.15	3.12	3.10	3.12	3.12	3.09	3.12	3.08
4	65.88	81.43	64.24	81.81	81.81	65.73	80.87	63.79
5	20.83	21.87	21.08	21.97	21.97	20.83	22.07	21.03
6	3.12	3.17	3.07	3.18	3.18	3.12	3.13	3.09
7	96.56	99.49	102.04	91.79	91.79	97.68	101.81	101.57
8	8.01	12.91	10.93	7.96	12.91	12.91	15.41	15.52
9	3.25	3.28	3.22	3.27	3.26	3.26	3.28	3.23

The equivalent SNR, η expression for 'larger-the-better' quality characteristics is given in equation (10) and SNR, η expression for 'smaller-the-better' quality characteristics is given in equation (11) as follows [15];

$$\eta = -10Log_{10}\left[\frac{1}{n}\sum\left(\frac{1}{Y_1^2}+\frac{1}{Y_2^2}+....+\frac{1}{Y_n^2}\right)\right] \quad (4)$$

where n is the number of tests in each experiment and Y is the output value of the refractive index change.

$$\eta = 10Log_{10}\left[\frac{1}{n}\sum\left(Y_1^2+Y_2^2+....+Y_n^2\right)\right] \quad (5)$$

where n is the number of tests in each experiment and Y is the output value of the free carrier absorption loss.

By applying eq. (4) and eq.(5), the SNR of each device for refractive index change and absorption loss were calculated and shown in Table 6. The SNR for the refractive index change and free carrier absorption loss are presented graphically in Fig. 3 and Fig. 4 respectively.

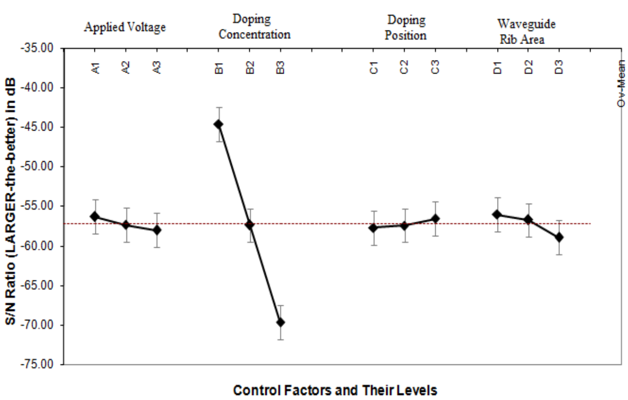

Fig. 3. SNR graph for Refractive Index Change.

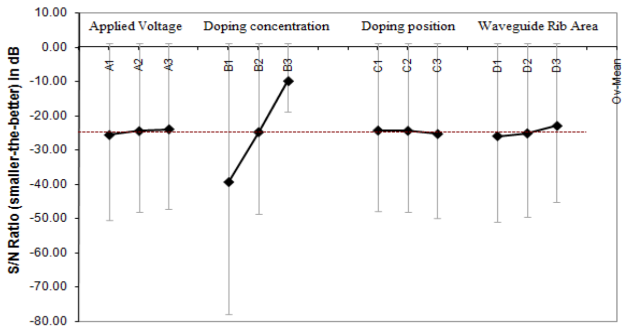

Fig. 4. SNR graph for Free Carrier Absorption Loss.

Table 6. SNR of Refractive Index Change and Free Carrier Absorption Loss.

Experiment Number	S/N Ratio (dB)	
	Refractive Index Change	Free Carrier Absorption Loss
1	-43.02	-41.36
2	-56.17	-26.04
3	-69.83	-9.87
4	-46.67	-37.31
5	-55.66	-26.64
6	-69.80	-9.91
7	-44.25	-39.93
8	-60.40	-22.10
9	-69.50	-10.26

ii. Analysis of Variance (ANOVA)

The effect of the applied voltage, doping position, doping concentration and waveguide rib area to the refractive index change and free carrier absorption loss of the modulator were obtained by decomposition of variance, which is named analysis of variance (ANOVA) [16]. According to results of the ANOVA for refractive index change in Table 7, process parameter B which is the applied voltage is the dominant factor which contributes 98% of the SNR value. The highest refractive index change is obtained when bias voltage of 1.0 V is used which corresponds to factor and level of B_1. It was also discovered that factors A, C and D were found to be insignificant (pooled) in the refractive index change characteristics. Finally, the optimized device design should have the following combinations $A_1B_1C_3D_1$ in order to obtain the highest refractive index change.

Table 7. ANOVA Result of Refractive Index Change.

Process Parameter	Degree of Freedom	Sum of Square	Mean square	Factor Effect on S/N Ratio (%)
A	2	4	2	0
B	2	942	471	98
C	2	2	1	0
D	2	14	7	1

The ANOVA's results for the free carrier absorption loss was also carried out and shown in Table 8. The result also shows that the process parameter B which is the applied voltage is the dominant factor which contributes 98% of the SNR value. The smallest free carrier absorption loss is obtained when bias voltage of 0.8 V is used which corresponds to factor and level of B_3.The factors A, C and D were also found to be insignificant (pooled) in the free carrier absorption loss characteristics. Therefore, the optimized device design should have the following combinations $A_3B_3C_1D_3$ in order to obtain the smallest free carrier absorption loss.

Table 8. ANOVA Result of Free Carrier Absorption Loss.

Process Parameter	Degree of Freedom	Sum of Square	Mean square	Factor Effect on S/N Ratio (%)
A	2	4	2	0
B	2	1307	653	98
C	2	2	1	0
D	2	14	7	1

iii. Confirmation test

The confirmation experiment is the final step to verify the optimal setting of the design parameter. The purpose is to validate the conclusions drawn during the ANOVA analysis section. 2 sets of confirmation test have been done in this study. The first set of confirmation test will validate the best settings of the control factors ($A_1B_1C_3D_1$) selected through the 'larger the better' refractive index change characteristic. The results is shown in Table 9. From the results the highest refractive index change of 0.00741 was achieved for noise factor combination as in Column #2 ($E_1F_1G_2H_2$). The refractive index change of the modulator has increased by 45.6% from the initial design. The S/N ratios for refractive index change after the optimization approaches are -71.28. The values are within the predicted value range of -66.74 to -72.28. Then, these setting is using to get the free carrier absorption loss. However, a large value for the free carrier absorption loss of 123.25dB/cm was obtained.

Table 9. Confirmation Test Result of Refractive Index Change.

Refractive Index Change								SNR (Larger-the-Best)
Δn_1	Δn_2	Δn_3	Δn_4	Δn_5	Δn_6	Δn_7	Δn_8	
6.81e-03	7.41e-03	6.39e-03	7.18e-03	6.85e-03	6.86e-03	6.98e-03	7.31e-03	54.1

The second confirmation test was also conducted. But this time, the best setting of of the control factor from 'smaller-the-better' free carrier absorption loss characteristic ($A_3B_3C_1D_3$) was used and the results are shown in Table 10. The table shows the smallest free carrier absorption loss is 2.18 dB/cm was achieved for noise factor combination as in Column #1 ($E_1F_1G_1H_1$). The S/N ratio of -8.32 obtained is within the predicted value and improves 95.3% from the initial design. Unfortunately, these settings will produce only 0.00024 of refractive index change which is too small.

Table 10. ANOVA Result of Free Carrier Absorption Loss.

Free Carrier Absorption Loss								SNR (Smaller-the-Best)
$\Delta\alpha_1$	$\Delta\alpha_2$	$\Delta\alpha_3$	$\Delta\alpha_4$	$\Delta\alpha_5$	$\Delta\alpha_6$	$\Delta\alpha_7$	$\Delta\alpha_8$	
2.19	2.57	2.66	2.95	2.58	2.19	2.95	2.65	-8.32

4.3 Optimal device

After confirmation test was done, the tuning of the best setting will be decided in order to design the optimal silicon phase modulator with balancing performance between refrective index change and free carrier absorption loss. The results from the confirmation test section have been taken into consideration in the determination of the best setting of control and noise factors. Six expriments have been conducted by varying the levels of factor (B) which is the applied voltage. Since other factors (A, C and D) are proven insignificant in ANOVA analysis, any levels of these control factors can be used. The influences of two types of noise combinations ($E_1F_1G_2H_2$) and $E_1F_1G_1H_1$) have been observed as well.

The results of 6 experiments mentioned are listed in Table 11. It is clearly seen that the results in colomn #2 and colomn #5 are the same. The similarity provides means that the $A_2B_2C_2D_2$ setting combination is robust. Finally, the combination of $A_2B_2C_2D_2$ is choosen as the best setting to produce desired optimal silicon waveguide phase modulator. This setting is selected because the device exibits insensitivity with the variance of noise. Optimal design of the modulator has successfully reduced the free carrier absorption loss by 75.56% (19.9 dB/cm) and remains high refractive index change (0.00155). These results indicate that the orthogonal array methodology using Taguchi method is a cost-effective method in predicting the optimum solution in finding the robust modeling for the optical SOI waveguide phase modulator.

Table 11. Results of tuning experiments for optimal setting parameters.

Experiment No.	**Control Factor**	**Noise Factor**	**Δn**	**Δα(dB/cm)**
1	$A_2B_1C_2D_2$	$E_1F_1G_1H_1$	*1.46e-03*	*18.56*
2	$A_2B_2C_2D_2$	$E_1F_1G_1H_1$	*1.55e-03*	*19.9*
3	$A_2B_3C_2D_2$	$E_1F_1G_1H_1$	*1.42e-03*	*18.02*
4	$A_2B_1C_2D_2$	$E_1F_1G_2H_2$	*1.54e-03*	*19.85*
5	$A_2B_2C_2D_2$	$E_1F_1G_2H_2$	*1.55e-03*	*19.9*
6	$A_2B_3C_2D_2$	$E_1F_1G_2H_2$	*1.56e-03*	*20.17*

5. Conclusions

As a conclusion, the robust design of SOI waveguide phase modulator was successfully modeled by using Taguchi Method in this paper. The good performance according to the desired design of the device have achieved with $A_2B_2C_2D_2$ of control factor combination. Analysis of variance (ANOVA) shows the applied voltage is the most significant process parameter based on 95% confidence level towards refractive index change and free carrier absorption loss responses.

Acknowledgments

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