Modeling Mach Zehnder Interferometer (MZI) Modulator on Silicon-On-Insulator (SOI)

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***Abstract*— This paper discusses the effects of different applied voltages on the performance of Mach Zehnder Interferometer (MZI) modulator on Silicon-On-Insulator (SOI). The analysis was done at a wavelength of 1550 nm. The phase modulator was implemented using the forward biased effect of the p-i-n structure. Meanwhile, the MMI splitter and combiner were utilized in order to develop the MZI structure. The design and simulation for the electrical structure were carried out using Athena and Atlas from Silvaco International. Besides, the OptiBPM and OptiSys from Optiwave Corporation were utilized for the optical structure. The analyzed output parameters include the extinction ratio (ER), the insertion loss and the modulation efficiency. It is observed that the application of lower voltage on the modulator displays the best overall performance.**

***Index Terms*—Mach Zehnder Modulator, forward biased effect, Silicon-On-Insulator, MMI**

I. Introduction

The Silicon-On-Insulator (SOI) has spurred profound interest as material for integrated optoelectronics. This situation is driven by the unique characteristics of the SOI, which include its transparency at the communications wavelengths of 1.3 µm and 1.55 µm, its high refractive index properties, and the possibility of integrating the optical circuitry with electronic circuitry; thus, making it suitable for optoelectronic applications at these wavelengths. The SOI wafers become popular platforms for photonic, electric and optoelectronic integrated circuits. SOI CMOS circuits benefit from reduced parasitic and absence of latch up; thus, enabling high-speed operation at low power. These are crucial requirements in modern telecommunication and computation systems [1], [2].

Demonstrations of silicon optical modulators based on forward biased effect, reverse biased effect, and accumulation effect on Silicon-On-Insulator have been done by various researchers[3]–[7]. Using the concept of diode p-i-n, silicon-based modulator with forward biased effect operates with forward bias voltage application. The use of this effect can overcome the problems faced by reverse biased and accumulation effects in terms of resistance and high capacitance devices for carrier buildup and a low carrier concentration in the active region as experienced by the carrier depletion effect. Thus, the forward biased effect is capable of exhibiting a large change in the refractive index with high extinction ratio (ER) [8], [9]. In addition, optical modulator with high ER value is important for long distance data transmission, bit error rate (BER) and good sensitivity detector [10]. Therefore, the carrier injection structure has the potential to be used as a silicon modulator for optical communication network applications.

The ER is defined by the ratio of maximum transmission intensity (I_{max}) to the minimum transmission intensity (I_{min}) which is given by:

$$10 \log (I_{max}/I_{min}) \tag{1}$$

Meanwhile, the insertion loss takes into account the optical power loss when the modulator is coupled to a photonic circuit. This factor has a significant impact because it involves the loss of the budget and overall connection system.

Optical modulator modulation efficiency is also one of the output parameters of the optical modulator. Lower value of the modulation efficiency relates to better performance of the optical modulator. Optical modulator modulation efficiency is represented by the following equation:

$$V_\pi L_\pi \tag{2}$$

where V_π is the voltage required to obtain a phase shift of π radians, and L_π refers to the length of the phase modulator required for a phase shift of π radians [11].

The self-imaging properties of multimode interference (MMI) are commonly employed in planar lightwave circuits to make compact power splitters, combiners, and Mach Zehnder interferometers with good tolerance to fabrication errors[12]. MMI operating principle based on the concept of self-imaging waveguide is the nature of the various modes. This concept led to the input signal is distributed evenly among the output waveguides[13]. Figure 1 depicts the MMI structure. Meanwhile, the value of length, L of the MMI depends on the value of the width of the MMI, W_e referring to the following equation:

$$L = \frac{4n_0 W_e^2}{3\lambda_0} \quad (3)$$

where W_e is the effective width of the MMI, n_0 is the effective refractive index and λ_0 is the vacuum wavelength [13].

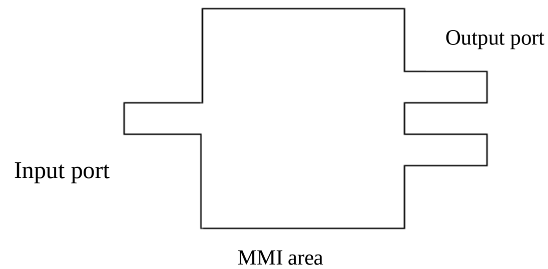

Figure 1: Structure of MMI device

One of the critical issues of the MZMs design is the applied voltage. Lower applied voltage is desirable as low voltage means low power consumption and less heat dissipation problems. In this paper, different voltages were applied in order to analyze the effects on the MZM modulator in terms of its extinction ratio (ER), insertion loss and the modulation efficiency.

II. Methodology

The design of the optical modulator consists of two parts. The first part is to develop the electrical structure of the optical modulator, also known as the phase modulator. The phase modulator utilizes the forward biased P-I-N structure as shown in Figure 2. The design was done by utilizing the Athena and Atlas software, from SILVACO international with the parameter values as depicted in Table 1.

Meanwhile, the second part of the design consists of developing the optical structure of the optical modulator. The MZI were used as the interferometric structure as shown in Figure 3. The values of the parameter are tabulated in Table 2.

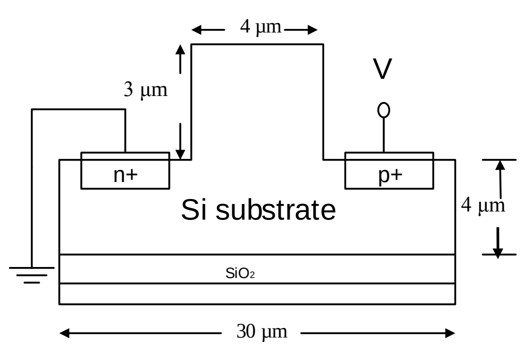

Figure 2: Structure of the phase modulator

Table 1
Parameter Values for Phase Modulator

Parameter	Values
Silicon refractive index	3.45
Silicon's background carrier (cm^{-3})	$1x10^{14}$
Holes' lifetime, τ_p (s)	$2x10^{-6}$
Electrons' lifetime, τ_n (s)	$2x10^{-6}$
Temperature (K)	300
Holes injection (cm^{-3})	$5x10^{17}$
Electrons injection (cm^{-3})	$5x10^{17}$

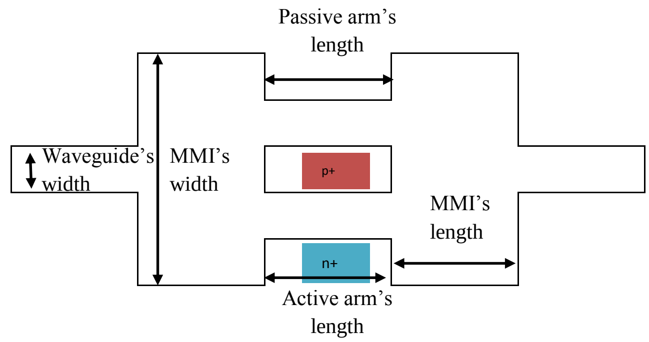

Figure 3: Schematic of the MZI optical modulator

Table 2
Parameter Values for MZI Modulator

Parameter	Values
MMI's width	38 µm
MMI's length	4283 µm
Waveguide's width	4 µm
Passive arm's length	1180 µm
Active arm's length	1000 µm
Applied Voltages	0.85,0.95,1.0V

III. Results and Discussion

The spectrum shift of the modulator with different applied voltages is shown in Figure 4. It is observed that at the wavelength range of 1550-1555 nm, the applied voltage of 0.85 V demonstrates the highest intensity change compared to other applied voltages.

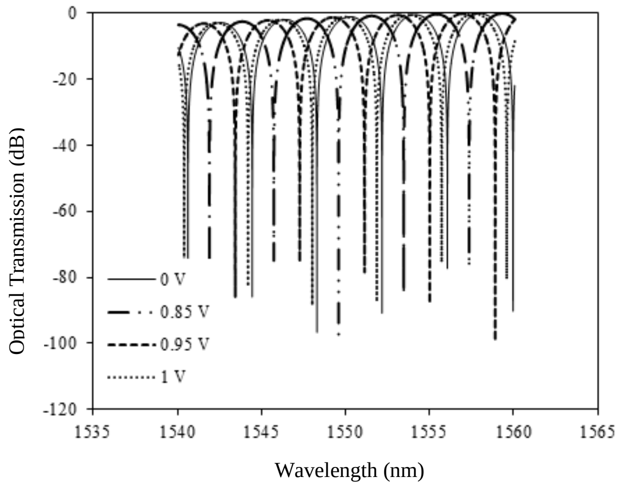

Figure 4: Spectrum shift of MZI modulator for different applied voltages.

Based on Figure 5, higher applied voltage diminishes the value of ER of the modulators. The gain of the voltage induced in the conducting phase modulator can cause an imbalance between the amplitude of the optical field and the two arms of the MZI. This results in a reduction of the ER when the biased voltage is increased.

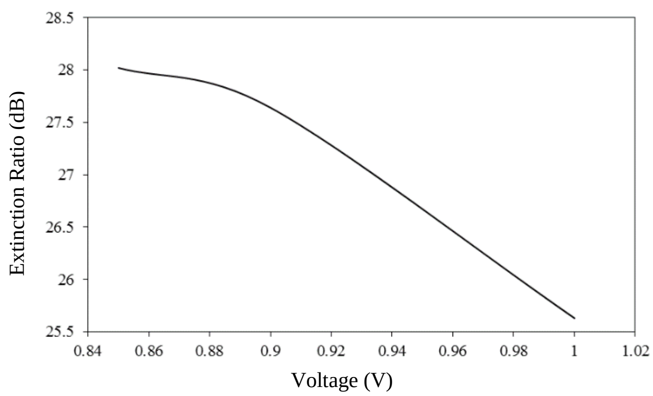

Figure 5: Extinction Ratio (ER) vs Applied Voltages

Figure 6 shows that the insertion loss is directly proportional to the applied voltage. Each of the applied voltage on the device represents the values of certain changes in the refractive index. The applied voltage of 1V represents the highest refractive index changes. Thus, the absorption loss, which is closely related to changes in the concentration of holes and electrons is also the highest. This situation contributes to the demonstration of the highest insertion loss when 1 V is applied to the MZI optical modulator.

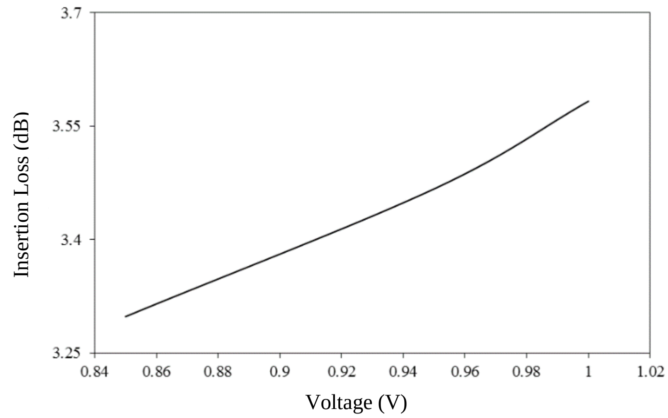

Figure 6: Insertion Loss vs Applied Voltages

Figure 7 depicts the relationship between the modulation efficiency with the biased voltage. Since lower value of modulation efficiency corresponds to a more efficient device, it is found that the efficiency of the device decreases with the increasing value of bias voltage. Although a large biased voltage supplying electrons and holes are more in the intrinsic region, this situation reduces the signal to noise ratio (S / N). Noise is a part of the loss; hence, this situation causes an increase in the insertion loss when the biased voltage is increased.

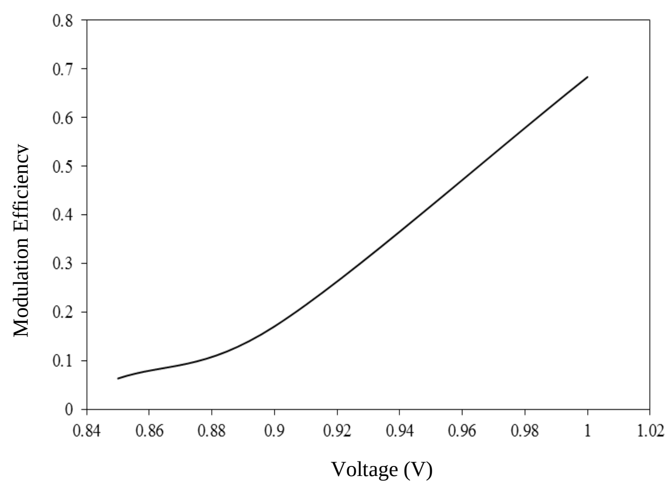

Figure 7: Modulation Efficiency vs Applied Voltages

Table 3 illustrates the simulation data for the different values of applied voltages. Overall, the values of the output parameters in the simulation are in agreement with the previous works [5], [14], [15].

It is shown that the biased voltage of 0.85 V demonstrates the best overall performance with ER of 28.02 dB, modulation efficiency of 0.06319V.cm and insertion loss of 3.298 dB. The devices exhibit a low insertion loss which is in the range of 3.2 – 3.6 dB. Meanwhile, the ER of the devices is at least 25 dB. In terms of efficiency, the least efficient device demonstrates the value of 0.68352 V.cm, while the most efficient device recorded 0.06319 V.cm.

Table 3
Simulation data for different values of applied voltages

Voltage (V)	ER (dB)	Modulation Efficiency (V.cm)	Insertion Loss (dB)
0.85	28.02	0.06319	3.298
0.95	27.64	0.17042	3.467
1.0	25.63	0.68352	3.583

IV. CONCLUSION

The performance of the MZI optical modulator on SOI has been investigated by varying the applied voltage. The device with the lowest voltage displays the best overall performance. The simulation work serves as vital reference for future work.

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