The performance analysis of different tapered structures of MMI couplers for MZI modulators on Silicon-On-Insulator (SOI)

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This paper reports the development of the Mach Zehnder Interferometer (MZI) optical modulator utilizing different tapered structures of the multimode interference (MMI) employing the Silicon-On-Insulator (SOI) technology. There are two parts involved in developing the MZI modulators which are the electrical and optical part. The P-I-P-I-N structure was used in the electrical part of the device. Meanwhile, in the optical part, the MMI couplers design structure was applied. There are three MMI structures being utilized in the optical section which are the non-tapered, linear tapered and the parabolic tapered MMI structure. All three designs were set to the same design parameters. The effect of using the different MMI design structure were analyzed in terms of its extinction ratio (ER), insertion loss (IL) and the modulation efficiency ($V_\pi L_\pi$). The parabolic tapered structure is recorded to have the highest ER, which is 33.33 dB and lowest IL 4.592 dB compared to the other design structure. For the modulation efficiency, all three designs demonstrated almost the same values which are within the range of 0.0565 V.cm to 0.0572 V.cm. The device modeling shows that the parabolic tapered structure gives the best performance. This is probably due to the tilting design which allows better propagation of optical signal towards the end of the device structure.

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1. Introduction

The multimode interference (MMI) couplers are one of possible components for the Mach Zehnder Interferometers (MZI) for splitting and combining light. MMI splitter and combiner have few advantages such as it has many-fold, with the main benefits being their ability to operate over a wide wavelength range [1], insensitivity to refractive index variations, and compact in size [2].

MZI is a fundamental device for various applications such as the optical sensors [3,4], optical filter [5], optical modulators, optical switches and optical add-drop multiplexer [6,7]. The MZI can also be integrated with the micro ring-resonators in order to reduce the modulation voltage and improve the linearity of the device [8,9]. This device has the best performances by having the larger optical bandwidth, low loss and also the design of MMI is less complicated compared with other structure [10–12].

Previous research on the tapered MMI structure to produce an optimized structure for MZI modulator has been carried out [13]. The size of the MMI structure can be reduced by using the tapered structure which allows the compatibility with other devices [14]. There are few types of tapered being analyzed, which are the linear tapered [15], parabolic tapered [16], exponential tapered [17], elliptical tapered [18] and co-sinusoidal tapered [19]. Zamil et. al. has discussed the comparisons of having different kind of tapered structure which can improve the performance of the devices and eventually leads to smaller geometries [20]. Whilst researches on tapered MMI structures have been carried out by previous researchers, there is still no study that compares the performance of non-tapered MMI devices and tapered MMI devices as MZI modulators on Silicon-On-Insulator (SOI) as yet.

Hence, this paper reports on the design and analysis of the non-tapered, linear tapered and parabolic MMI structures for MZI modulators on Silicon-On-Insulator (SOI). The performance of the structures is compared in terms of the extinction ratio, insertion loss and modulation efficiency.

The design of the optical modulator consists of two parts which are the electrical and the optical part. In electrical part, the phase modulation based on carrier injection effect occurs. Meanwhile, in the optical part, the design structure of the MMI couplers is being utilized to develop the MZI structure.

2. Multimode interference device

a. Self-Imaging Principle

MMI device is synonymous with the self-imaging principle. The self-imaging principle is described in details in [21]. The central structure of MMI is designed as a waveguide to support the light propagation from the beginning through the end of the waveguide structure.

The width and length of the MMI are related to each other. Using the available value of the MMI width, the calculations of the length of the MMI region required for the imaging of the structure are gained by using Equation 1:

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \simeq \frac{4 n_r W_e^2}{3\lambda_0} \quad (1)$$

Where n_r is the effective refractive index of the waveguides, W_e is the effective width of the MMI region, and λ_o is the free-space wavelength [21]. The illustration of the self-imaging principle are being produced by [12], [13], [15–17], [20–25]. The theory produces structures which are able to propagate light in any number of modes which are generally referred as NxM MMI couplers. N is referred as the input and M is the output of the MMI waveguides.

b. The design structure analysis

The reduction of the width and length of the MMI structure can be seen using the tapered MMI structure. Besides that, the extinction ratio (ER), insertion loss (IL) and modulation efficiency ($V_\pi L_\pi$) are the features being carried out to compare the performance improvement of different design structures. The insertion loss can be defined as:

$$IL = 10 \, log_{10} \frac{P_{in}}{P_{out}} \quad (2)$$

where the P_{in} is the power input of the MMI and P_{out} is the power at the output waveguide. Through simulation, IL can be extracted by the rate of change of the output and input power being computed in OptiSystem software. The modulation efficiency of the MZI modulator can be calculated by using Equation 3.

$$Modulation\ Efficiency = V_\pi L_\pi \quad (3)$$

Where the value of V_π is the voltage of the active region of the phase modulator and the length L_π can be obtained using the following equation.

$$L_\pi = \frac{\Delta\phi(\lambda)}{2\pi\Delta n} \quad (4)$$

where, λ is the wavelength, Δn is the rate of change of refractive index and Δϕ is the phase shift [26]. The value of the phase shift, Δϕ can be extracted using the optical transmission's waveform of the passive and active phase modulators. Other data that can be extracted directly from the waveforms are the ER, free spectral-range (FSR) and Δλ. By using these data, the phase shift can be calculated by using the Equation 5:

$$\Delta\phi = \frac{2\pi\Delta nL}{FSR} \quad (5)$$

3. Design and methodology

The optical modulator design consists of two structures; the electrical structure and the optical structure. The first part will be the electrical structure which also known as the phase modulator. Meanwhile, the other part is the optical structure; in which the design of the modulator has taken place. Both structures are designed to let the electrical and optical signals propagate through the device.

a. Electrical structure

Fig. 1 shows the lateral view of P-I-P-I-N structure use in the phase modulator. The design was prepared in SILVACO by using Athena and Atlas software. This design structure consists of intrinsic region, and p-type or n-type semiconductor regions. Silicon-on-Insulator (SOI) is used as a substrate for the formation of the P-I-P-I-N structure. The structure is formed in order to control electrically the injection of electrons and holes into the intrinsic region. These will allow the signal to propagate perfectly along the waveguides.

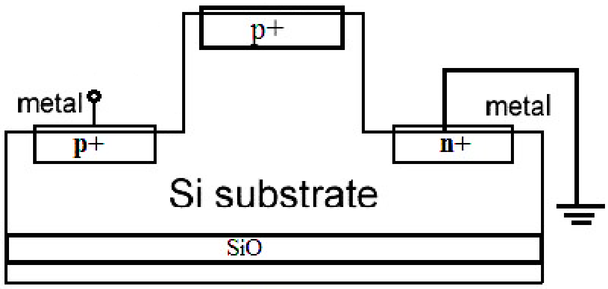

Fig. 1. The lateral view of PIPIN structure used as phase modulator

b. Optical structure

In this paper, the optical modulator has been designed by using the OptiBPM software. Then, this structure is combined in the OptiSys software to create the MZI structure and for optical characterization purposes.

Table 1. The parameter values for the MZI modulator

Parameters	Values (μm)
MMI's width	38
MMI's length	4859
Waveguide's width	5
Passive arm's length	790
Active arm's length	600

Table 1 shows the design parameters that are being used in the design simulation. The specifications are the same for all three designs. The parameters used are the fixed variable in order to observe the changes in performance while changing the design structure.

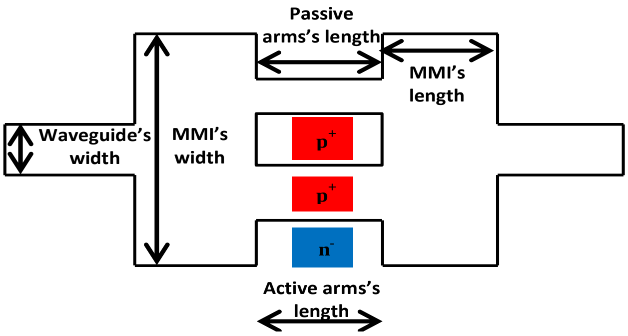

Fig. 2. The MZI optical modulator

Fig. 2 illustrates the basic structure of the MZI modulator that is used in the simulation. The structure was varied at the input splitter and combiner of the MZI modulator.

Figs. 3, 4 and 5 show different MMI structures of non-tapered, linear tapered and parabolic tapered for the design and simulation of MMI splitter. Fig. 3 shows the non-tapered MMI structure. The MMI design utilizes the 1×2 MMI structure. Fig. 4 shows the MMI tapered structure. The tapered design was applied at the output waveguides in order to observe the difference in its output performance. The parabolic tapered as depicted in Fig. 5 was designed at the same location as in the linear tapered structure. Moreover, both tapered structures have the same start and end width of 10 μm and 5 μm, respectively.

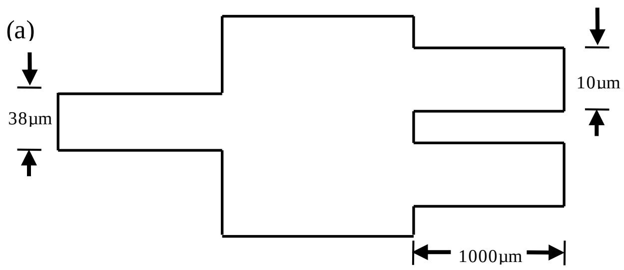

Fig. 3. Non-tapered MMI structure

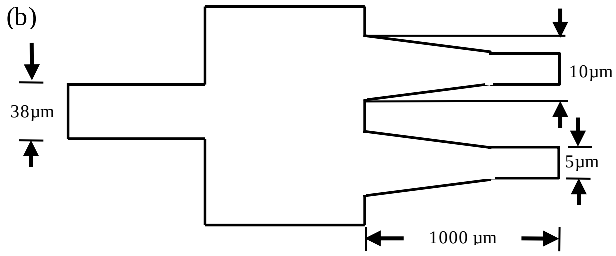

Fig. 4. Linear tapered MMI structure

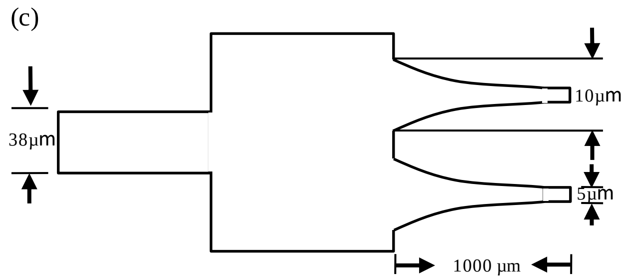

Fig. 5. Parabolic tapered MMI structure

4. Results and discussions

The performance of the simulation of the MZI modulator structures is observed in terms of its ER, IL and the modulation efficiency, $V_{\pi}L_{\pi}$.

Fig. 6 shows the simulated performance of the MZI modulator of the non-tapered, linear tapered, and parabolic tapered of MMI structures. The different types of MMI structures have obtained significantly different performance.

The parabolic tapered structure gives the best ER among the other structure as shown in Fig. 6(a). Since the parabolic structure has a tilted waveguide, it can provide better splitting of the optical signal rather than using the linear tapered structure. Thus, it allows the phase tilt of the optical signal along a coordinate system to the end of the structure [27]. Fig. 6(b) depicts the parabolic tapered structure with the lowest IL of 4.592 dB compared to other structures. The non-tapered and linear tapered structures have higher IL with 5.728 dB and 5.725 dB, respectively. This is due to the narrow path attained by the tapered structure that leads to a better propagation of optical signal towards the end of the device. Previous research by An et. al. recorded the same range of IL which was within 3.8 to 6.8 dB [28].

Fig. 6(c) shows the modulation efficiency between these three MMI structures. These structures have obtained similar modulation efficiency, which ranging between 0.0565 V.cm to 0.0571 V.cm. This is due to the same active arm's length used by all the structures throughout the simulation.

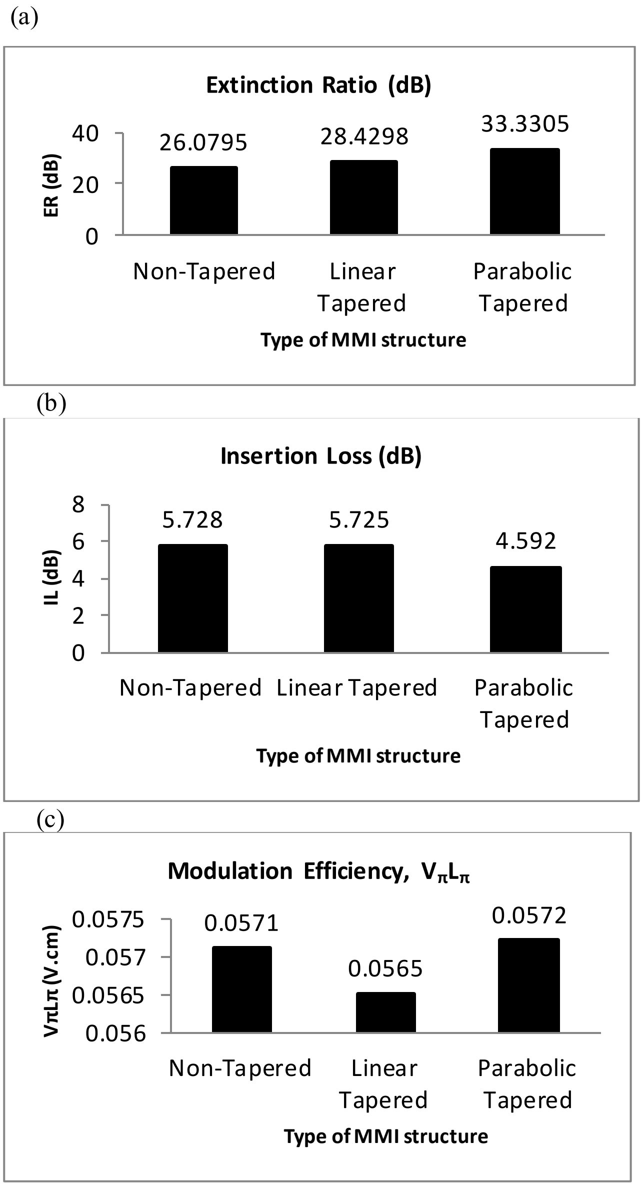

Fig. 6. The simulated performance of MZI modulator. (a) extinction ratio (ER), (b) insertion loss (IL), and (c)modulation efficiency.

Table 2 represents the performance of the MZI modulators using different type of MMI structure; non-tapered, linear tapered and parabolic tapered structure. The parabolic tapered device demonstrated the highest ER value which is 33.3305 dB. Besides that, the parabolic tapered structure also exhibited the lowest IL of 4.592 dB, which are 1.1 dB lower than the other two structures. However, for the modulation efficiency, all three structures showed almost the same values, ranging from 0.0565 V.cm to 0.0572 V.cm.

Table 2. Performance of the modulator using different MMI structure

MMI Structure	Extinction Ratio (dB)	Insertion Loss (dB)	Modulation Efficiency, $V_\pi L_\pi$ (V.cm)
Non-Tapered	26.0795	5.728	0.0571
Linear Tapered	28.4298	5.725	**0.0565**
Parabolic Tapered	**33.3305**	**4.592**	0.0572

5. Conclusion

By having the tapered MMI structure, a better MZI modulator device could be obtained. The tapered design structure is important in reducing the bending loss in MMI design. Besides that, it could also increase the optical signal propagation. Overall, the parabolic tapered device has a better ER of 33.3305 dB and IL of 4.592 dB compared to other MMI structure design simulated in this paper. The design structure of MZI modulator with better extinction ratio and low loss has been obtained by using parabolic tapered MMI structure. The study offers some important insights in designing the MZI modulator design on Silicon-On-Insulator (SOI).

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