

## Optical Interconnect Waveguide in Electronic Circuit

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### ABSTRACT

The increasing demand in silicon nano-photonics has encouraged many researchers to put more efforts to explore the feasibility of using optics in the communication medium in order to replace the conventional electrical interconnects (EIs). In this paper, we proposed a SOI- based waveguide in the optical interconnect (OI) link at an operating frequency of 1550nm to work as an interconnection path in a circuit. The performance capability of the OI link was tested using a two-stage CE amplifier to work as the interconnection path from the 1st stage to the 2nd stage amplifier. In term of optical performances, the optical waveguide interconnect managed to achieve a single mode condition for a TE mode and fulfill the receiver sensitivity of a photodiode. While, in term of electrical performance, a two-stage CE amplifier is able to produce a high gain, a wide bandwidth and high slew rate. The proposed implementation of the OIs waveguide is successfully enhance the performance of the two-stage CE amplifier as well as the analog electronic circuit applications.

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## 1. INTRODUCTION

Interconnects in the integrated circuit (IC) are used to connect transistors and other electronic components on a chip [1]. The performance of the conventional copper interconnects degrades substantially due to the scaling dimensions in the Complementary Metal Oxide Semiconductor (CMOS) technology [2]. According to International Technology Roadmaps for Semiconductor (ITRS), the circuits to be manufactured in the nanometer scale will contain more than a billion transistors [3] and causing the requirement of large number of interconnects [4]. Therefore, the optical interconnects (OIs) have been considered as an alternative solution for the electrical interconnects (EIs) [5]. Moreover, silicon nano-photonics is a key technology for realizing that such optical components can be fabricated with Si CMOS compatible device processes [6]. The advantage of OI link compared to EIs is able to provide a high bandwidth density, minimizing lower power consumption, as well as decreasing interconnect delays and noise [7-11].

The theory of OI was introduced by Goodman in 1984 [12]. Figure 1 shows the basic block diagram of OI link on a very large scale integrated (VLSI) electronic circuit. The main components of OI are off-chip CW source, modulator, an optical waveguide and a photodetector. The most famous waveguide material are Polymer [13], Silicon-on-Insulator (SOI) [14] and Indium Gallium Arsenide Phosphide (InGaAsP). The applications of OI technology are in the computer system, mobile devices, as well as other electronic circuit systems.

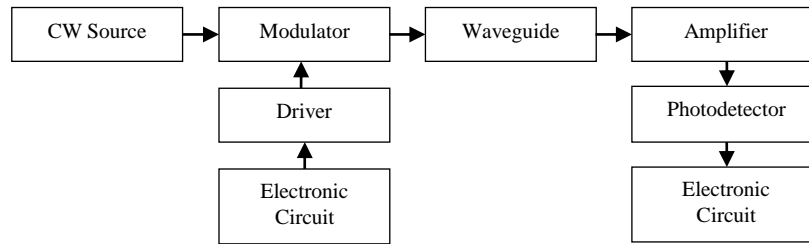


Figure 1. Block Diagram of OI link [12]

In this work, the SOI-based waveguide is implemented on the OI link with high-speed frequency of 1550nm wavelength. This paper aims to evaluate both the electrical and optical performance of each device involved in the OI link. The electrical performance can be measured in an electrical part such as an electronic circuit; a two-stage CE amplifier. Meanwhile, optical performances can be measured in the optical parts such as the CW source, modulator, optical waveguide and photodetector.

## 2. RESEARCH METHOD

There are two simulation steps in this methodology; first, is the simulation of SOI waveguide and the second step is the implementation of the SOI waveguide in the OI link using a two-stage CE amplifier circuit.

### 2.1. Simulation of the OI Waveguide

A simple expression of a large rib waveguide to produce the SMC output is introduced by Soref et.al. [15] [16] in order to obtain a low propagation loss and delay. The expression is as follows:

$$\frac{W}{H} \leq 0.3 + \frac{r}{\sqrt{1-(r)^2}} \quad (1)$$

$$\text{For } 0.5 \leq r \leq 1 \quad (2)$$

Where  $r$  is the ratio of a slab height to the overall rib height, and  $W/H$  is the ratio of a waveguide to the overall rib height. The analysis of the waveguides in Equation (1) is limited to the shallow etched ribs as per Equation (2). Figure 2 (a) presents a layout cross section of a large rib waveguide and (b) presents a SMC output of the SOI waveguide.

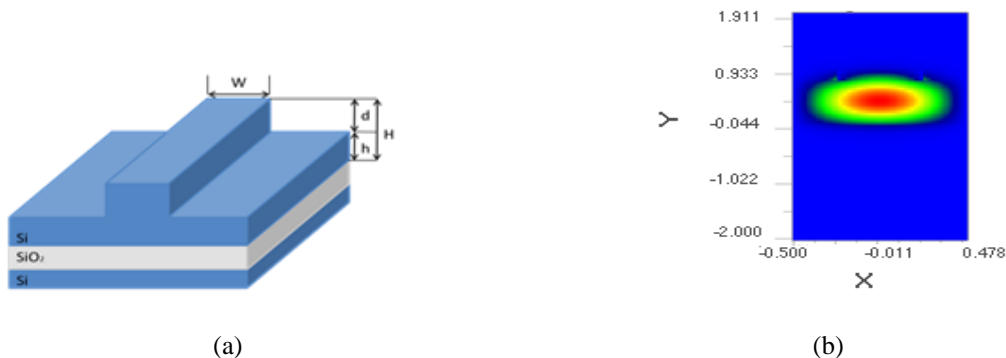


Figure 2. (a) Layout Cross Section of SOI Waveguide and (b) SMC Output of SOI Waveguide

The SOI waveguide was designed and simulated in an OptiBPM version 9. The material of the waveguide core was silicon (Si) with a refractive index,  $n_{Si}=3.477$ , while the waveguide substrate was silicon dioxide (SiO<sub>2</sub>) with  $n_{SiO_2}=1.444$ . Therefore, the effective index ( $n_{eff}$ ) produced from this SOI waveguide was 3.308 [17].

## 2.2. OI Link

Figure 3 shows the schematic circuit of the two-stage CE amplifier with the implementation of SOI waveguide in the OI link. The length of the optical waveguide was set to 10000 $\mu\text{m}$ . Referring to Figure 3, the electrical signal from the 1st stage amplifier output was converted to an optical signal using a Mach-Zehnder modulator and was transmitted in an optical signal through the optical waveguide. Then the photodetector detected the signal and was converted back to the electrical signal. Therefore, the electrical signal is the input of the 1st stage amplifier and the output signal of 2nd stage amplifier.

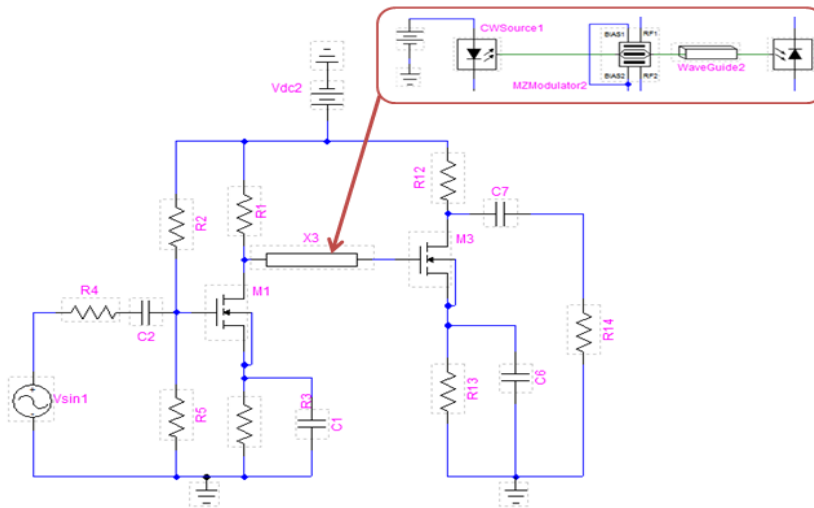


Figure 3. Integration of OI Link in the Two-Stage CE Amplifier

## 3. RESULTS AND ANALYSIS

The implementation of the OI link in the two-stage CE amplifier has been designed and simulated using the SPICE tool. During the analysis, the optical performance was measured at the optical component, while the electrical performance was measured at the electronic component, respectively.

### 3.1. Optical Performances

The optical performance measured was the line bandwidth of the spectrum profile, power loss and delay in the optical waveguide, power degradation in OI link, and receiver sensitivity of the photodetector. The frequency wavelength was set to 1550nm and data bit rates were equal to 10Gbps.

#### 3.1.1. Line Bandwidth of the Spectrum Profile

Figures 4 (a) and (b) show the spectrum profile of the CW source and modulator with three different levels, -3dB, -10dB, and -20dB level.

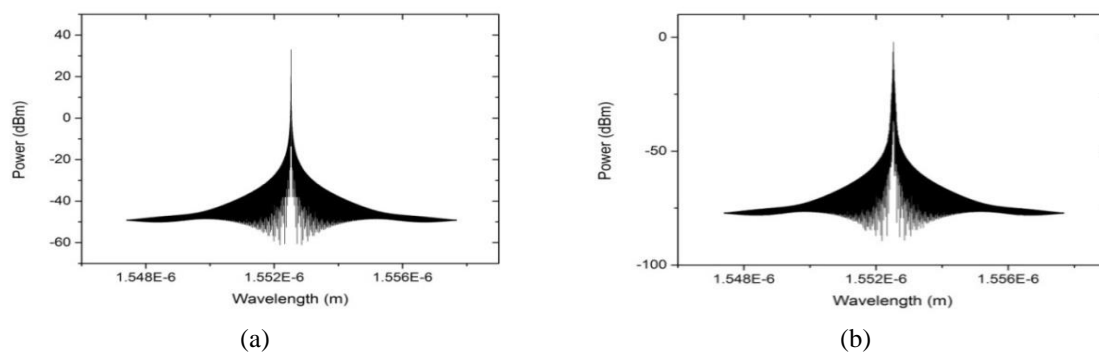


Figure 4. (a) CW Source Spectrum Profile and (b) MZ Modulator Spectrum Profile

The line bandwidth for the CW source and MZ modulator was tabulated in Table 1. It can be seen that the modulated signal from the MZ modulator has a wider line width for all levels compared to the CW Source.

Table 1. The Performance of Line Bwidth for CW Source and MZ Modulator

Component	Line Width(nm)		
	-3dB level	-10dB level	-20dB level
CW Source	0.0004	0.002	0.008
MZ modulator	0.0008	0.019	0.4

### 3.1.2. Power loss in the Optical Waveguide and Power Degradation in the OI Link

The power loss of the modulator and optical waveguide can be calculated via Equation (3) and (4):

$$P_{loss(mod)} = P_{mod(output)} - P_{CW(output)} \quad (3)$$

$$P_{loss(waveguide)} = P_{waveguide(output)} - P_{mod(output)} \quad (4)$$

Figure 5 shows the power degradation of the OI link. The output power for CW Source was 34.034 dBm, MZ modulator was 2.952dBm, SOI waveguide was 0.820dBm and PIN photodetector was 19.857 dBm. Therefore, the total power loss using SOI waveguide was 2.132dBm.

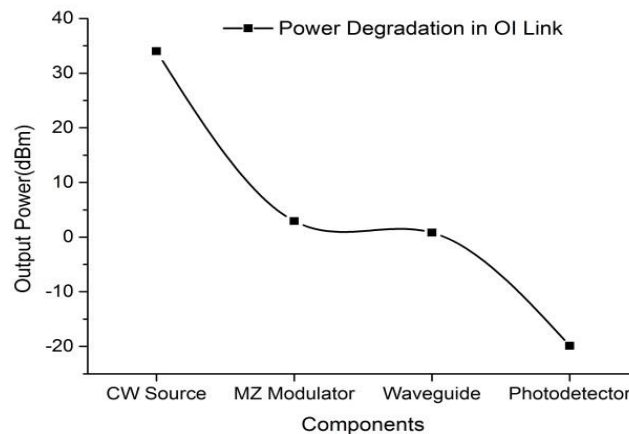


Figure 5. Power Degradation in OI link

### 3.1.3. Delay in Optical Waveguide

The output delay through the optical waveguide is expressed via Equation (5):

$$t_{wg} = n_{eff} \frac{L}{c} \quad (5)$$

where  $n_{eff}$  is the effective index of the mode in the waveguide medium,  $L$  is the length of the waveguide and  $c$  is the speed of light in vacuum. For  $r$  is equal to  $0.5\mu\text{m}$ , the delay is  $10.8\text{ps}$  [18].

### 3.1.4. Receiver Sensitivity of the Photodetector

The photodetector used is a PIN photodiode which can execute high bandwidth and sensitivity. For a photodiode material, Ge is more suitable due to a high speed for a short distance communication and lower cost. A  $-19.857\text{dBm}$  of power sensitivity is produced in the simulation.

### 3.2. Electrical Performances

The electrical performance measured was transient analysis, gain, frequency bandwidth, slew rate and propagation delay.

#### 3.2.1. Transient Analysis

Figure 6 (a) and (b) show the input and output signals of the two-stage CE amplifier using OI. The input signal of the two- stage CE amplifier using OI was set to 12.5mV-peak, while the output signal swung roughly at 4.52V-peak.

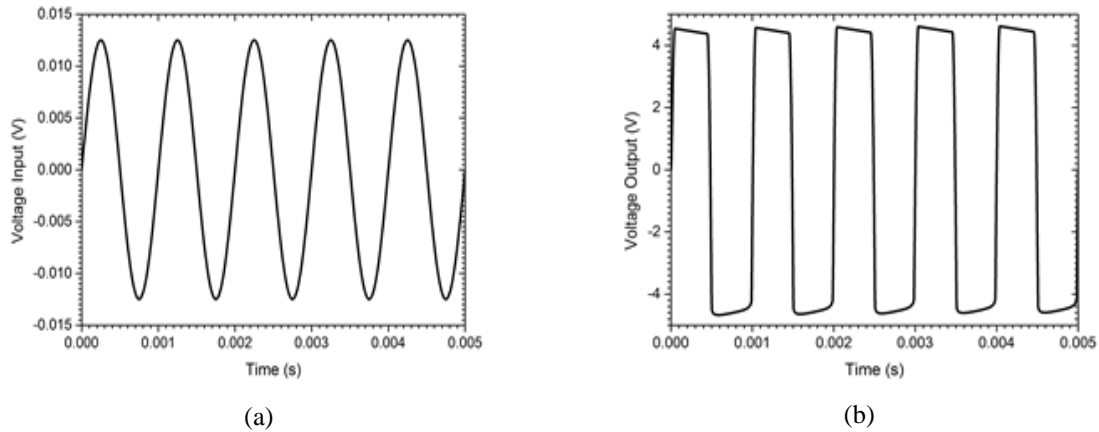


Figure 6. (a) Transient Input and (b) Transient Output of the Two-Stage CE Amplifier using OI

#### 3.2.2. Gain

Gain of the amplifier refers to the ratio of output voltage to the input voltage. It represents how much an amplifier can amplify a given signal. Gain can be simply expressed in terms of a dimensionless quantity or in decibel (dB). Gains are calculated via Equation (6):

$$G = \frac{V_{out}}{V_{in}} \quad (6)$$

In dB, the voltage gain is expressed by Equation (7):

$$A_v(dB) = 20 \log \frac{V_{out}}{V_{in}} \quad (7)$$

Using Equations (6) and (7), the gain of the two- stage CE amplifier using OI was 51.16 and 54.5, respectively.

#### 3.2.3. Frequency Bandwidth

The bandwidth ( $BW$ ) of the amplifier represents the range of the frequency that amplifier can amplify effectively. The bandwidth of an amplifier is the difference between the lower half point,  $f_L$  and upper half point,  $f_H$  known as the frequency limits of an amplifier. The bandwidth is given via Equation (8):

$$Bandwidth(BW) = f_H - f_L \quad (8)$$

Figure 7 shows the frequency response of the two-stage CE amplifier. The -3dB points on a frequency response curve tagged P1 and P2 were the  $f_L$  and  $f_H$  respectively. Based on Figure 7, the  $f_L$  was 130Hz, whereas the  $f_H$  was 80 kHz. Therefore, the  $BW$  was 79.8 kHz.

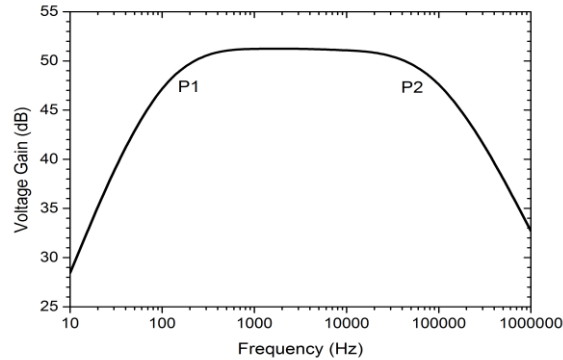


Figure 7. Frequency Bandwidth of Two-Stage CE Amplifier

### 3.2.4. Slew Rate

Slew rate,  $SR$  of an amplifier is defined as the maximum rate of a change output voltage per unit of time. It represents how rapidly the output of an amplifier can be changed in response to the change in the input. The slew rate of the amplifier can be calculated using Equation (9):

$$SR = \frac{\Delta V_{out}}{\Delta t} \quad (9)$$

where  $\Delta V_{out}$  is  $V_{max} - (-V_{max})$  and the units are in  $V/\mu s$ . The higher the value of the slew rate, the faster the output can change and more easily reproduce high frequency signals. Using Equation (9), the  $SR$  of the two-stage CE amplifier using OI was  $24V/\mu s$ .

### 3.2.5. Propagation Delay for Different Interconnect Length

Figure 8 presents a performance analysis of the OIs for the varying interconnects length. The propagation delay was analyzed from the output pin of the amplifier to the input pin of the next amplifier. The length value, on the other hand, was identified based on the optical waveguide length.

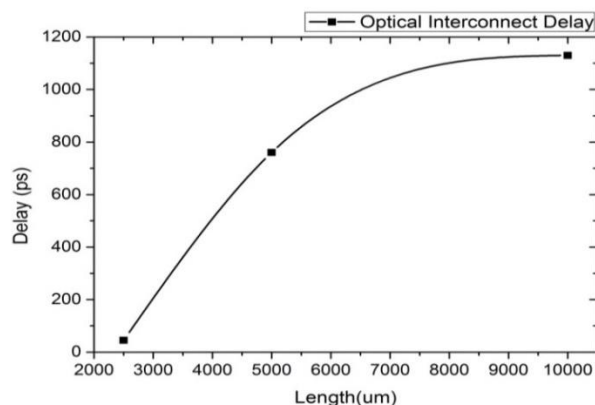


Figure 8. Propagation Delay of the Two-Stage CE Amplifier

#### 4. CONCLUSION

The integration of OI link in the analog electronic circuit was successfully performed by combining the electrical and optical components in the SPICE tools. The results were discussed from the viewpoint of the optical and electrical performances of the two-stage CE amplifier using OI. From the analysis, the used of SOI waveguide in OI the link produces high gain, bandwidth, slew rate and lower delay of the two-stage CE amplifier circuit. It is concluded that the SOI-based OI waveguide is a prominent solution for the short distance applications and one of the best solutions for the future VLSI interconnects.

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#### REFERENCES

- [1] M.G. Kumar, Y. Agrawal, and R. Chandel. Carbon Nanotube Interconnects – A Promising Solution for VLSI Circuits. *IETE Journal of Education*. 2016; 57(2): 46-6.
- [2] J.H. Collet, F. Caignet, F. Sellaye, and D. Litaize. Performance Constraints for Onchip Optical Interconnects. *IEEE Journal of Selected Topics in Quantum Electronics*. 2013; 9: 425–432.
- [3] D. Dunggal, G. Singh and M. Kaur. A Unified Codex Scheme for Reduction of Area and Crosstalk in RC and RLC Modeled Interconnects using both Bus Encoding and Shielding Insertion Technique. *International Journal of Electrical and Computer Engineering (IJECE)*. 2013; 3(4): 542-532.
- [4] D. Kaur and V. Sulochana. Crosstalk Minimization in VLSI Interconnects. *International Journal of Reconfigurable and Embedded Systems (IJRES)*. 2013; 2(2): 89-98.
- [5] P. Dong, W. Qian, S. Liao, H. Liang, C. Kung, and N. Feng. *Low Loss Silicon Waveguides for Application of Optical Interconnects*. Proc. of IEEE Photonics Society Summer Topicals. 2010: 191–192.
- [6] J. Fujukata, K. Nishi, A. Gomyo, J. Ushida, T. Ishi, H. Yukawa, D. Okamoto, M. Nakada, T. Shimizu, M. Kinoshita, K. Nose, M. Nakada, T. Shimizu, M. Kinoshita, K. Nose, M. Mizuno, T. Tsuchizawa, T. Watanabe, K. Yamada, S. Itabashi, and K. Ohashi. LSI On-Chip Optical Interconnection with Si Nano-Photonics. *IEICE Transaction Electron*. 2008; E91-C(2): 131-137.
- [7] B.D.A.B. Miller. *Device Requirements for Optical Interconnects to Silicon Chips*. Proc. of the IEEE. 2009; 97(7): 1166-1185.
- [8] G. Chen, H. Chen, M. Haurylau, N.A. Nelson, D.H. Albonese, P.M. Fauchet, and E.G. Friedman. *On-chip copper-based vs. optical interconnects: Delay uncertainty, latency, power, and bandwidth density comparative predictions*. International Interconnect Technology. Conference (IITC). 2006: 39–41.
- [9] G. Chen, H. Chen, M. Haurylau, N. Nelson, D. Albonese, P. M. Fauchet, and E. G. Friedman. *Electrical and optical on-chip interconnects in scaled microprocessors*. Proc. of the IEEE Int. Symp. Circuits Syst. 2005; 3: 2514–2517.
- [10] J. Chen, N. Bamiedakis, P.P. Vasil, T.J. Edwards, C.T.A. Brown, R.V. Penty, and I.H. White. High-Bandwidth and Large Coupling Tolerance Graded-Index Multimode Polymer Waveguides for On-Board High-Speed Optical Interconnects. *Journal of Lightwave Technology*. 2016; 34(12): 2934–2940.
- [11] P.K. Shen, A. Hosseini, X. Xu, Y. Hei, Z. Pan, and R.T. Chen. Multiple-Input Multiple-Output Enabled Large Bandwidth Density On-Chip Optical Interconnect. *Journal of Lightwave Technology*, 2016; 34(12): 2969–2974.
- [12] J.W. Goodman, F.J. Leonberger, S.Y. Kung and R.A. Athale. *Optical Interconnections for VLSI*. Proc. of the IEEE. 1984; 72(7): 850-866.
- [13] K. Niewegłowski and K.J. Wolter. *Optical Analysis of Short-Distance Optical Interconnect on the PCB-Level*. in Electronics System Integration Technology Conference, Dresden, Germany. 2006; 1: 392–397.
- [14] M.K.S.S. Saini. All-optical logic gate in silicon nanowire optical waveguides. *IET Circuits Devices System*. 2011; 5(2): 115–122.
- [15] H. Huang, K. Liu, B. Qi, and V. J. Sorger. Re-analysis of single-mode conditions for Silicon rib waveguides at 1550 nm wavelength. *Journal of Lightwave Technology*. 2016; 34(16): 3811-3817.
- [16] J. Lousteau, D. Furniss, A.B. Seddon, T.M. Benson, S. Member, A. Vukovic, and P. Sewell, “The Single-Mode Condition for Silicon-on-Insulator Optical Rib Waveguides with Large Cross Section. *Journal of Lightwave*. 2004; 22(8): 1923–1929.
- [17] S.S.M. Sallah, S.H.M. Ali, P.S. Menon, N. Juhari, M.S. Islam, and S.A. Ahmad. *Investigation on Optical Interconnect (OI) Link Performance using External Modulator*. Proc. of IEEE Regional Symposium on Micro and Nanoelectronics (RSM). 2015: 1-4.
- [18] S.S.M. Sallah, S.H.M. Ali, P.S. Menon, N. Juhari and M. S. Islam. *Delay Analysis in Symmetrical SOI-Based Rib Waveguide for High Speed Optical Interconnect*. in IEEE 6<sup>th</sup> International Conference on Photonics (ICP) . 2016: 1-3.

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