Travelling Wave Mach-Zehnder ModulatorPhotonics Integrated Circuit: A Performance Study

Radhika Ramesh[1], Netra Dalvi [2], Pravin Joshi [3]
[1,2,3]Fiber Optic Services (FOS), Mumbai, India
www.foservice.com
[1]radhika.ramesh@foservice.com, [2]netra.dalvi@foservice.com, [3]phj@foservice.com

***Abstract*: Photonic Modulators are an essential element in optical transmitter. This study focus on the performance of a Travelling-Wave Mach-Zehnder Modulator (TW-MZM) PIC and its sensitivity to reflection due to impedance mismatch in the travelling-wave electrode. The impact of Run-to-Run(RTR) and Wafer-to-Wafer(WTW) variations in foundry process on the performance of transmitter chip using a TW-MZM is also studied using Synopsys RSoft OptSIM®**

Keyword:Photonic Integrated Circuit, Silicon-Photonics, Travelling Wave,Bit Error Rate, Effective Refractive Index, Extinction Ratio, Eye-diagram,Optical Modulator.

1. Introduction

Modern optical communication system demands higher bandwidth and bit rate with current systems operating at 40Gbps. A simplest approach is to use a direct modulated laser. However, this direct modulation technique limits bit-rate. The relaxation oscillation of laser and packaging parasitic induction and capacitance limits the practical modulating frequency up to 10GHz. Also the frequency chirp limits the performance of the optical communication system by reducing the effective bandwidth of the fiber. For long haul application of higher bit rate, external modulation are an attractive alternative to direct modulated laser. Here the laser output is passed through an external device, hence the unwanted effects of direct modulated of laser are avoided. Also, the recent attention in silicon photonics, a scalable platform for integration of photonics, electronics and micro-optics using CMOS fabrication technique, fabricating highly complex and integrated systems are possible. External modulation in silicon is typically accomplished by a change in the effective index or a change in absorption. The changes in effective index leads to changes in the phase of the optical wave which can be further transformed into changes in intensity.MZ-Si modulator finds extensive application in data communication due to their relative thermal insensitivity and wide optical bandwidth.

If identical phase shift is experienced by both arms of MZ modulator, light interferes constructively resulting in maximum possible light out of the interferometer.

$$\Delta\phi = [\beta]L = \left[\frac{2\pi}{\lambda_0}\,\Delta n_{eff}\right]L$$

$\lambda_0$is free space wavelength and β the phase constant of an optical wave with λ_0

In this paper, we are modelling a TW-MZM using discrete photonic integrated circuit(PIC) elements. The performance of TW-MZM depend on the matching between effective index of the optical waveguide and electrical transmission line. A perfect matching result in nearly infinite bandwidth while a 10% mismatch heavily affect the performance. The travelling wave nature of the modulator makes it sensitive to reflection due to impedance mismatch in the travelling wave electrode. This can be same for an optical waveguide. Here it is assumed that effective index of optical waveguide remains constant and doesn't introduce any reflection.

The modulator performance when wafer-to-wafer (WTW) and run-to-run (RTR) variation in Si photonic foundry process due to impedance mismatch is also examined using RSoft's OptSIM Circuit® layout. Complex signal interaction such as reflection and resonance in PICs can be modelled in OptSIMthat otherwise are impossible to model in conventional systems modelling tool.

2. System Details

2.1 Traveling Wave Mach-Zehnder modulator PIC

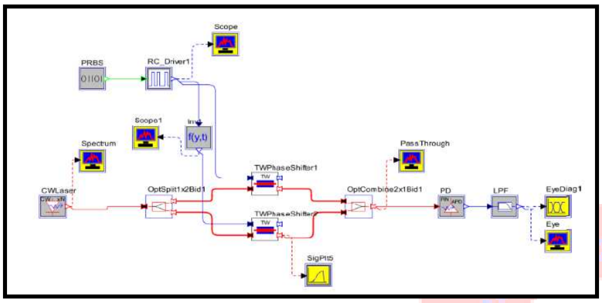


Fig No: - 2.1 Layout of a Traveling Wave Mach-Zehnder modulator PIC

A TW-MZM is modelled using discrete PIC elements as in fig 2.1. The layout comprises of bidirectional PIC elements such as two traveling wave optical phase shifters, 1x2 optical splitter and 2x1 combiner with user-defined power ratio. Each traveling wave phase shifter has an optical waveguide and a surrounding electrical transmission line introducing change in waveguide's refractive index and propagation loss. The continuous wave (CW) light is modulated by an electrical signal derived from PRBS data followed by an electrical RZ driver. The inverter model provides push-pull electrical bias to one of the electrodes compared to the other. At the output of the TW-MZM PIC, a photodiode is connected followed by an electrical filter and a scope.

The performance of the TW-MZM depends on the matching between the effective index of the optical waveguide and the electrical transmission line. The value of optical effective index and electrical transmission line are chosen to be 3 and 3.2 respectively. The length of the waveguide is chosen to be 1e-2 and CW laser is operated at a wavelength of 1.31e-6.

2.2Reflection sensitivity of TW-MZM

The sensitivity to reflection due to impedance mismatch in the travelling wave electrode as well as optical waveguide is another factor limiting device bandwidth. The effective index of the optical waveguide is assumed to remain a constant without any reflections.

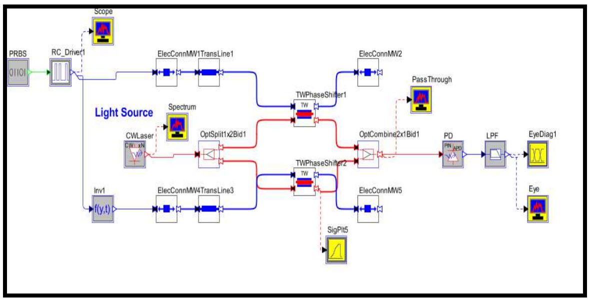


Fig No: - 2.2 Layout of a Traveling Wave Mach-Zehnder modulator PIC with microwave circuit connecting the electrodes to the generator and load impedances

Fig 2.2shows the layout including a microwave circuit for the traveling electrodes connections composed of a transmission line, a first impedance mismatch between the generator and the phase shifter electrode, and a second impedance mismatch between the phase shifter electrode and the load. The default values of generator, travelling wave electrode and load impedance is set to 50ohm.

2.3Impact of Silicon Photonic Foundry on TW-MZM PIC

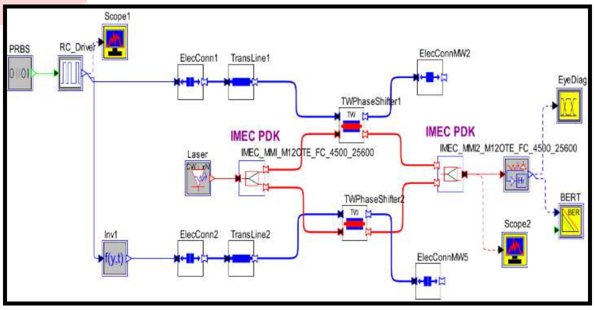


Fig No: - 2.3 Layout of the transmitter chip using TW-MZM.

The layout consists of IMEC foundry process design kit (PDK) elements for the photonic components for the splitter and combiner; and transmission line elements for the RF electrodes. A back-to-back receiver is used to estimate the performance of the transmitter chip. This study focuses on the performance impairments due to the impedance mismatches as a result of the wafer-to-wafer (WTW) and run-to-run (RTR) variations in the silicon photonic foundry processes. The impedance mismatch can be between the generator and the phase shifter electrode, or between the phase shifter electrode and the load, or both. The mismatch in impedance between the electrode and the load is studied at a wavelength of 1.55e-06.

3. Result & Discussion

Fig 3.1.1 shows modulated optical signal (left) and its spectrum (right) and Fig 3.1.2 shows electrical signal and eye diagram at the receiving end.

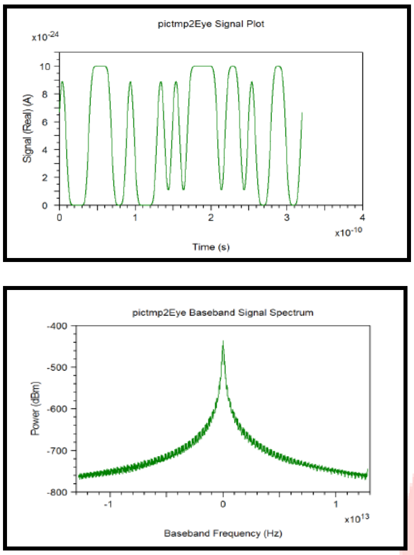


Fig No: - 3.1.1 TW-MZM output signal (left) and spectrum (right)

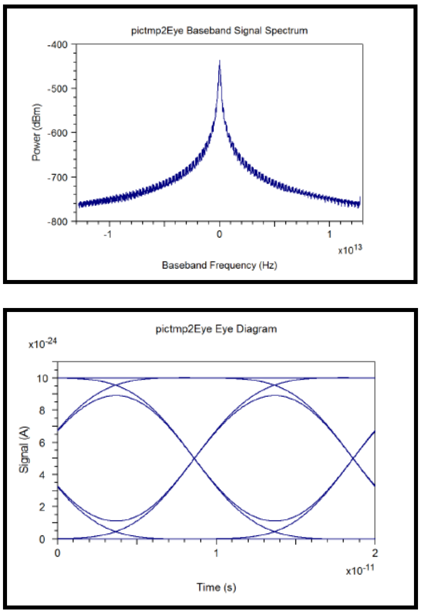


Fig No: - 3.1.2 Detected signal (top) and receiver eye diagram (bottom)

A parametric scan setup on the electrical effective index variations from 3 to 4 in 0.2intervals keeping the optical effective index constant to 3 was studied. The change in the eye opening is pronounced. Fig 3.1.3 shows the eye for effective index values of 3.0 and 3.4 respectively.

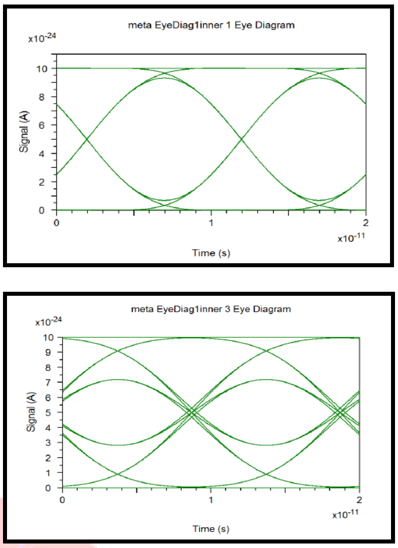
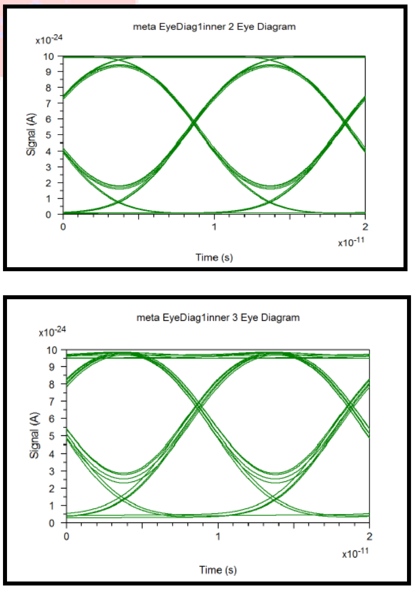


Fig No : -3.1.3 Received eye diagram for optical effective index equal to 3.0 and electrical effective index equal to 3.0 (top) and 3.4 (bottom)

A parametric scan was carried on load impedance from 0-50 Ohm. The fig 3.2.1 shows the eye diagram where the impact of electrical microwave reflection from load can be analysed.



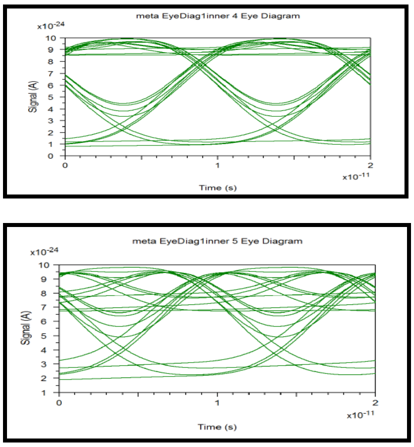


Fig No : - 3.2.2 Eye diagrams at the receiver with traveling wave electrode impedance equal to 50 Ohm and load impedance equal to 40, 30 , 20 and 10 Ohm (from top to bottom in sequence)

Figure 3.3.1 shows the effect of the impedance between the electrode and the load is analysed from the modulator's extinction ratio as measured from the optical eye at the modulator output.

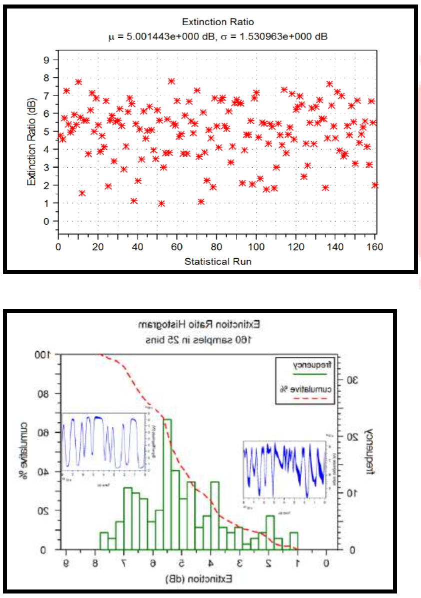


Fig No: -3.3.1 Distribution (top) and histogram (bottom) for the extinction ratio at the modulator output

The extinction ratio is seen to vary from as low as 1dB to 8dB. Fig 3.3.2 shows the effect of the impedance mismatch between the electrode and the load on the BER of back-to-back received signal at the modulator.

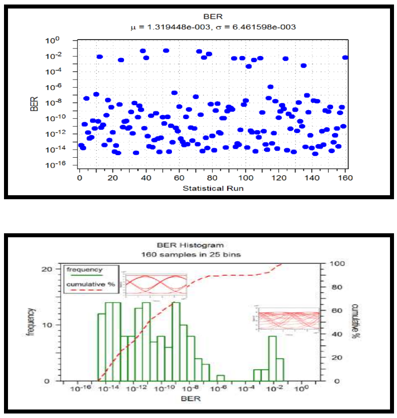


Fig No: -3.3.2 Distribution (top) and histogram (bottom) for the BER at back-to-back received signal

While the BER was observed to be in the $10^{-10}$to 10^{-14} range, it goes as high as 0.1 and as low as10^{-15} due to the stochastic nature of the process variations.

4. Conclusion

The performance of TW-MZM at a wavelength of 1.31e-06 was studied. A perfect matching between effective index of optical waveguide and electrical transmission line give nearly infinite bandwidth while a 10% mismatchheavily affect performance. The analysis of eye diagram for load impedance value of 10 to 40 ohm clearly show the impact of electrical microwave reflection originating from load on system performance.

Taking into account the tolerance in fabrication process is important to estimate the foundry yield and also help system and chip designer to understand the performance bound. Modelling at the device and circuit level help in learning the most sensitivity design parameter that are susceptibility to foundry technology and can have great impact on process yield and overall system performance.

5. References

1. *Hongtao Lin, Okechukwu Ogbuu, Jifeng Liu, Lin Zhang, Jurgen Michel, and Juejun Hu, "Breaking the energy-bandwidth limit of electro-optic modulators: Theory and a device proposal," Journal Of Lightwave Technology, vol. 31, no. 24, December 15, 2013, pg. 4029-40*
2. *Synopsys RSoft OptSim application notes*
3. *K. Kawara, T. Kitoh, H. Jumoni, T. Nozawa and M. Yomagibashi "New Traveling-Wave Electrode Mach-Zehnder Optical modulator with 20Ghz Bandwidth and 4.7V driving voltage at 1.52um wavelength" Electron Lett. Vol. 25, No. 20, Sep 1989, pp. 1382-1383*
4. *Baehr-Jones, Tom, etal "Ultralow drive voltage silicon traveling-wave modulator" Optics Express20.11 ;12014-12020*