

Hybrid Silicon Photonic Circuits and Transceiver for 56Gb/s NRZ 2.2km Transmission over Single Mode Fiber

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Abstract Using hybrid integration of electronics and silicon photonics integrated circuits, we demonstrate the generation and detection of up to 56Gb/s NRZ optical signals over 2km standard single mode fiber at 1310nm wavelength. The link operates error free at 40Gb/s and under KR4 FEC threshold at 56Gb/s.

Introduction

Silicon optical devices (modulators, Germanium waveguide photodetectors) at 10/25/28Gb/s data rates have been demonstrated and have been introduced commercially^{1,2}. Progress towards achieving generation and detection of optical signals at rates larger than 50 Gb/s have also been reported³⁻⁵.

Ethernet and fibre channel have converged at 25.78Gb/s and 28Gb/s serial rates. While these datarates can be addressed with mature directly modulated III/V lasers (DML) (VCSEL/MMF and DFB/SMF) and meet current fiber optic link standards and customer requirements, it is not clear today that DML technologies will be able to quickly scale beyond 28Gbps serial rate.

This work aims at demonstrating 1310nm NRZ serial 40Gb/s to 56Gb/s duplex single mode fiber (SMF) optical link using Silicon Photonic technology transmit and receive optical devices from STMicroelectronics PIC25G silicon photonics technology⁶. The silicon photonic IC is packaged and integrated into a CFP4 transceiver.

Silicon photonic hybrid IC

The 4x8mm integrated circuit is heterogeneous silicon technologies 3D IC composed of two stacked ICs connected with fine pitch copper pillars (μ -Cu-pillars, 20 μ m diameter, 40 μ m pitch with less than 10fF and 10pH parastics)⁷. The electronic IC (EIC) is flip-chipped onto the photonic/optical IC (PIC or OIC). Optical signals (single mode fiber array and CW lasers) are vertically coupled to the PIC via grating couplers available in STMicroelectronics silicon photonics technology. Two types of gratings are used. Single Polarization Grating Couplers (SPGC) are used on the transmitter output and CW laser input. Polarization Splitting Grating Couplers (PSGC) are used on the receiver side. SPGC have approximately 2dB insertion loss and 20nm 1dB bandwidth around the 1310nm peak wavelength. PSGC have approximately 4dB insertion loss and 20nm 1dB bandwidth around the 1310nm peak wavelength. Wide bandwidth ultra-low capacitance waveguide germanium

photodetectors and carrier depletion high-speed phase modulators are also available in the technology.

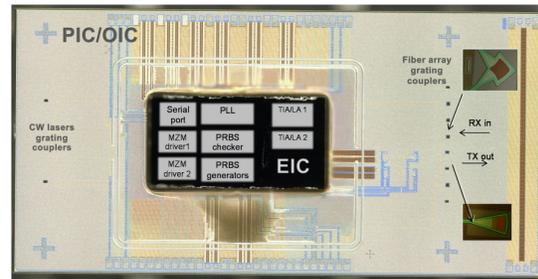


Fig. 1: OIC / EIC IC stack

The EIC consists of two MZM drivers and two TIA/LA for the transmitters and receivers. The IC offers PRBS 9 generators and a PRBS 9 checker for high-speed built-in testing capability.

Traveling Wave Electrodes (TWE) Mach-Zehnder Modulator (MZM) design

The PN junction carrier depletion high speed phase modulator used in the MZM exhibits a 10.5deg/mm phase shift under 2.5V bias ($V\pi.1 = 4V.cm$) and a low insertion loss $\propto \alpha_{optical}$ of 0.55dB/mm. This corresponds to a $V\pi.L. \propto \alpha_{optical}$ of 22V.dB figure of merit (FOM)⁸.

The MZI voltage to optical power transfer is:

$$P_o(t) = \frac{P_i}{2} \left[1 + \cos\left(\frac{\Delta V(t)}{V_{\pi mzm}} \pi\right) \right] e^{-\alpha_{optical} \cdot L} \quad (1)$$

where P_o and P_i are the modulator output and input optical power, $V_{\pi mzm} = (V_{\pi} \cdot l)/L$, L the modulator length and $\Delta V = V_{arm1} - V_{arm2}$ the modulator differential voltage.

Using the equation above, maximum OMA (Optical Modulation Amplitude) is achieved at $\pi/2$ bias point on the transfer curve for a 7mm long modulator.

Unfortunately, the lumped electrodes model is not valid for long electrodes and for speeds of 40Gb/s and above because the silicon optical waveguide propagation delay of the optical signal is $\sim 11.4ps/mm$. Traveling Wave Electrodes (TWE) or distributed driver

architectures (or a combination of both) are traditionally used.

In order to achieve maximum electro-optical bandwidth, the velocities of the electrical driving signal and optical wave must be matched. By periodically loading transmission line electrodes (Z_0, τ_0), with PN carrier depletion phase modulator sections, the loaded transmission line transmission characteristics ($Z_{loaded}, \tau_{loaded}$), are altered:

$$Z_0 = \sqrt{\frac{L_0}{C_0}}, \tau_0 = \sqrt{L_0 \cdot C_0} \quad (2)$$

with Z_0 the impedance and τ_0 the propagation delay $\sim 6.4\text{ps/mm}$ of the unloaded electrodes.

$$Z_{loaded} = \sqrt{\frac{L_0}{C_0 + C_{load}}}, \tau_{loaded} = \sqrt{L_0 \cdot (C_0 + C_{load})} \quad (3)$$

with Z_{loaded} the impedance and τ_{loaded} the propagation delay $\sim 11.4\text{ps/mm}$ (to match the optical signal) of the loaded electrodes. Modulator capacitance is approximately 220fF/mm at 2V reverse bias with a series resistance of $\sim 10\text{ohm}\cdot\text{mm}$. For RF electrical and optical waves velocity matching, the TWE unloaded electrodes are 350ohm and the loaded electrodes 20ohm for a differential drive as shown Fig 3 and 4.

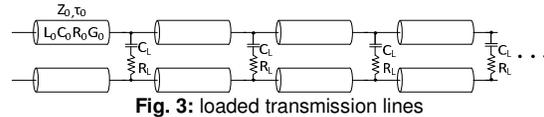


Fig. 3: loaded transmission lines

Taking R_0 (transmission line loss, skin effect) and R_L (PN diode series resistance) into account, the loaded TWE $\gamma_{RF} = \alpha_{RF} + j\beta_{RF}$ complex propagation parameter can be expressed as:

$$\gamma_{RF} = \sqrt{(R_0 + j\omega L_0)(G_T + j\omega(C_0 + C_T))} \quad (4)$$

with $C_T = \frac{2C_L}{1 + R_L^2 C_L^2 \omega^2}, G_T = \frac{R_L}{2} \left(1 + \frac{1}{R_L^2 C_L^2 \omega^2}\right)$

The TWE α_{RF} RF loss shows that the skin loss dominates below 28GHz and modulator loss above 28GHz RF loss at 28GHz is $\sim 4\text{dB/mm}$. Evidently, both modulator access resistance and skin loss have to be minimized to achieve large bandwidth. Unfortunately, these parameters are, for the most part, set by the technology and on

chip transmission lines. Transmitter equalization is provided by the driver.

The total amount of phase shift at the end of the two MZM arms is the cumulative phase shift of all the modulator sections along the two arms and can be calculated by integrating the voltage drive along the TWE. We find that the MZM insertion loss caused by RF losses at a given frequency is:

$$\frac{(1 - e^{-\alpha_{RF}(f)L})}{\alpha_{RF}(f)L} \quad (5)$$

At high frequencies, as the TWE losses caused by skin loss and the modulator access resistance become significant, increasing the length of the modulator no longer produces additional phase shift and the efficiency of the modulator does not improve. Taking this into account, for $\alpha_{RF}(28\text{GHz}) = 4\text{dB/mm}$, the maximum OMA achieved at $\pi/2$ bias point on the MZM transfer curve is achieved with a $\sim 3.5\text{mm}$ long modulator as shown Fig. 5.

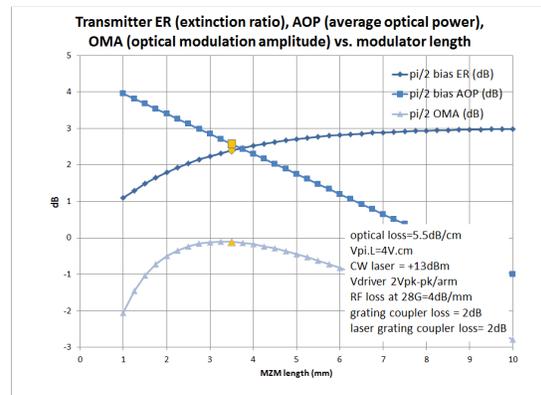


Fig. 5: Expected transmitter ER, AOP, OMA

The PIC MZM TWE chosen length is 3.36mm and composed of 12 $280\mu\text{m}$ modulator sections. The 350ohm transmission lines are 6μ metal4 over metal1 microstrips. The driver is AC coupled on the anode side and DC coupled on the cathode side. Reverse bias of 2V is provided by the driver. The driver circuit delivers 2Vpk-pk/arm . Automatic MZM biasing circuitry sets the MZM to maximum OMA.

CW laser, fiber array and the IC are assembled into a CFP4 transceiver for testing purpose.

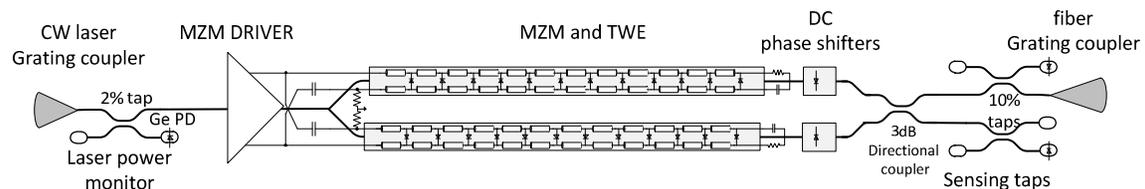


Fig. 4: MZM differential TWE and differential drive

Measurement results

Total RX/TX power dissipation including CW laser is less than 750mW per channel (600mW TX/150mW RX).

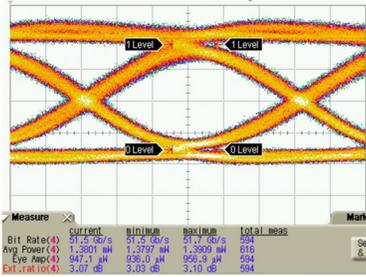


Fig. 6: 51.56Gb/s, PRBS9 TX optical eye Transmitter optical eye diagrams lab measurements show an excellent correlation between simulation and measurement.

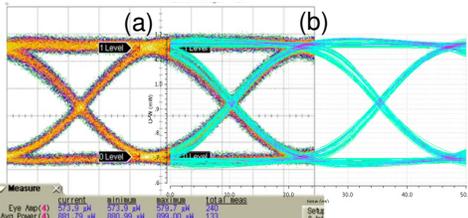


Fig. 7: 40Gb/s, PRBS9 TX optical eye diagram at $\pi/2$ bias

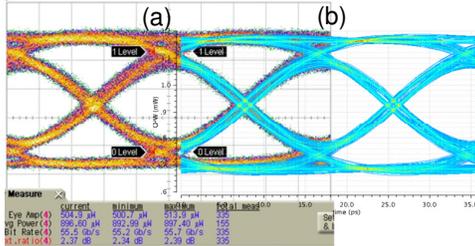


Fig. 8: 56Gb/s, PRBS9 optical TX eye diagram at $\pi/2$ bias (a) Measurement, (b) Simulation Measured PRBS9 receiver OMA sensitivity at 10^{-12} BER and 40Gb/s is -6dBm. 56Gb/s. Receiver OMA sensitivity at 10^{-5} BER is above -6dBm.

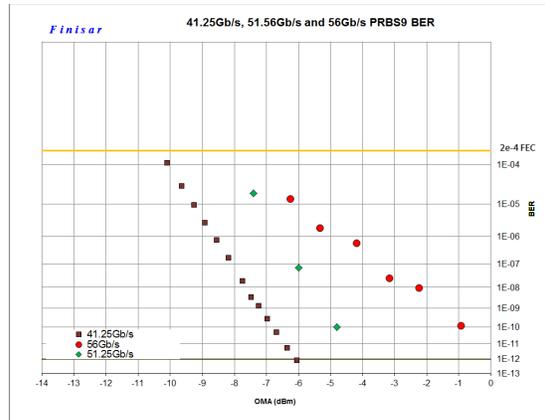


Fig. 9: Receiver BER vs. OMA using the on-chip PRBS checker, 41.25Gb/s, 51.56Gb/s and 56Gb/s

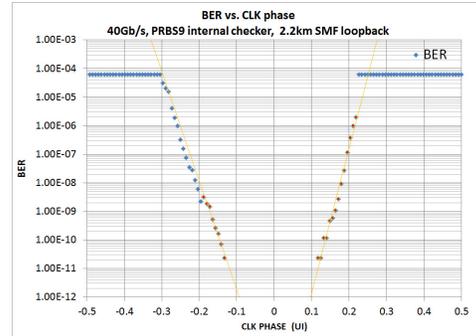


Fig. 10: Receiver horizontal eye opening using the on-chip PRBS checker, 41.25Gb/s 2.2km SMF

Conclusions

This work demonstrates silicon photonics technology performance for NRZ transmissions above 40Gb/s. This is the first fully integrated silicon photonics transceiver operating above 40Gb/s. Further work will focus on minimizing the insertion losses and improve the transmitter extinction ratio using distributed driver architecture.

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