 

# 40GBaud PAM4 silicon Mach-Zehnder modulator boosted by a heterogeneously integrated SOA with 10dB-gain

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**Abstract:** We report a silicon IQ modulator integrated with a III-V/Si semiconductor optical amplifier (SOA) at the output. We demonstrate 40GBaud PAM4 operation of one of the Mach Zehnder modulators with an SOA gain of 10dB.

## 1. Introduction

In 2019, the OIF detailed an implementation agreement for an Integrated Coherent Transmit-Receive Optical Sub Assembly (IC-TROSA) targeting coherent applications with dual polarization (DP) and symbol rates up to 64Gbaud [1]. The aggressive form factor puts tight integration constraints on the optical components. Such reduced footprints can only be achieved with silicon photonics (SiPho) and indium phosphide (InP) integrated optics.

InP Mach Zehnder modulators (MZMs) exhibit insertion loss (IL) < 5 dB, $V_\pi$ < 4 V, and bandwidth (BW) > 35GHz [2], but it is challenging to manipulate the optical polarization on InP platforms. Therefore, assembly with external devices is required, leading to additional losses and complexity. SiPho platform offers light polarization management together with integrated MZMs but the latter have reduced performances compared to InP implementations, with typical IL of ~6 dB IL, $V_\pi$ of ~6V and BW ~30 GHz. Overall, when implemented as coherent transmitters, both technologies suffer from high fibre-to-fibre losses: the total losses from the input laser to the output of the IQ modulator is typically about 20 dB (3dB split between the local oscillator (LO) and IQ modulator, 3 dB split between TE and TM polarizations, 6 dB split and combine loss for the IQ modulator, IL of the MZM at maximum transmission, and additional passive and assembly losses). The use of SOA has been proposed [3] to boost the output of an InP IQ modulator. The SOA was used as a fibre coupled device, and 16 and 64QAM operation was successfully demonstrated at 64Gbaud. This showed that SOAs can be used as booster amplifiers to increase transmitter output power with a low OSNR penalty.

Here, for the first time, we report a transmitter that heterogeneously integrates a Si IQ MZM with a III-V/Si SOA. Integrating the SOA on chip has two benefits: in addition to the reduced form factor, the "zero-loss" transition from the Silicon waveguide to the SOA waveguide enables to limit signal-to-noise ratio (SNR) degradation of the amplified signal as compared to fibre coupled SOA with inherent additional loss due to SOA-waveguide to fibre coupling. We demonstrate the benefits of the SOA by operating one of the nested MZMs with PAM4 modulation at 40Gbaud.

## 2. Heterogeneous III-V/Si integration platform and Integrated Transmitter Circuit

The authors of [4] recently reported on the heterogeneous integration, on a silicon platform, of a membrane InGaAsP MZM with an SOA. NRZ 40 Gbps operation was demonstrated. In [5], we reported on our fabrication flow enabling the heterogeneous integration of III-V DFB lasers at the backside of standard SiPho base wafers by means of III-V molecular bonding. The transmitter described herein makes use of the same fabrication flow, with the final cross section represented in Figure 1(a). The III-V stack forming the active section of the SOA has five InGaAlAs quantum wells (QW).

Figure 1(b) shows the schematics of the integrated coherent transmitter: the two nested MZMs 'Mod I' and 'Mod Q' are balanced modulators. Each comprises two arms using high speed 3mm long Si PN phase modulators, driven in a SGS push pull configuration. The heaters 'HI' and 'HQ' enable setting the phase difference between their two arms to $\pi/2$ or $\pi$ (to set the modulator at the 'quadrature' point or at 'carrier suppression respectively). The heater 'HIQ' is intended to set the relative phase between 'Mod I' and 'Mod Q' to any value. The III-V/Si SOA is located at one of the two outputs of the IQ modulator ('OUT IQ b') while the second output ('OUT IQ a') serves as the reference to measure the SOA gain. Light is coupled into the transmitter chip through grating couplers (GC). Figure 1(c) shows the optical micrograph of the IQ MZM and SOA. The chip size is only 4 x 1 mm².

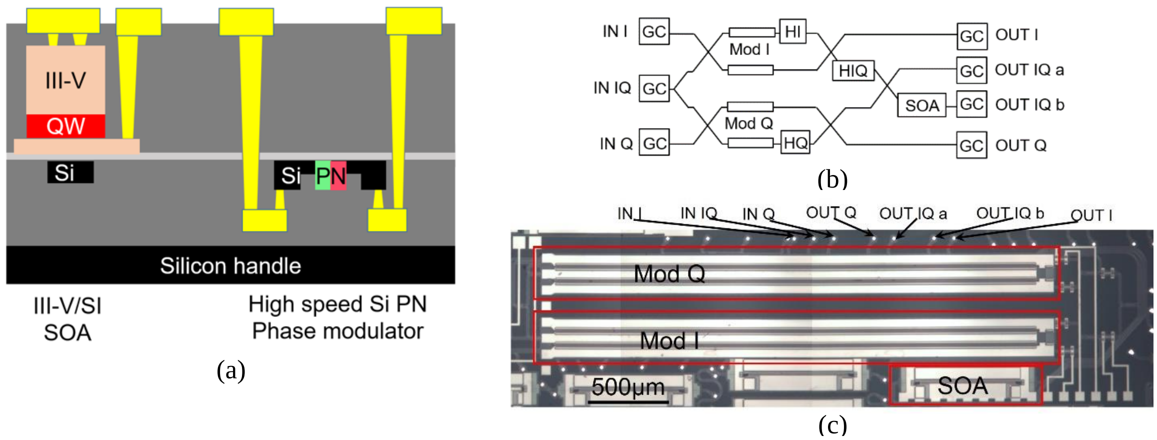


Fig. 1: (a) Cross section of the integrated Transmitter. (b) Schematics of the Integrated Transmitter: Si IQ modulator with Integrated SOA. (c) The optical micrograph of the circuit.

### 3. MZM Characterization.

We characterized the DC tuning efficiency and loss of the standalone MZMs. For ‘Mod I’, the measured $V_\pi$ is 6.5 V, with an insertion loss of -7.5dB, not including the 9 dB losses of the input and output grating couplers.

The S11 and S21 of one arm of the ‘Mod I’ modulator are reported in Figure 2(a). The -3dB EO BW of the phase modulator is ~35 GHz for a -2.5V negative bias of the PN junction. The -7dB S11 is relatively high: this is because the S11 measurement could not be done in a differential mode with our vector network analyser (VNA), leading to non-properly terminated electrodes.

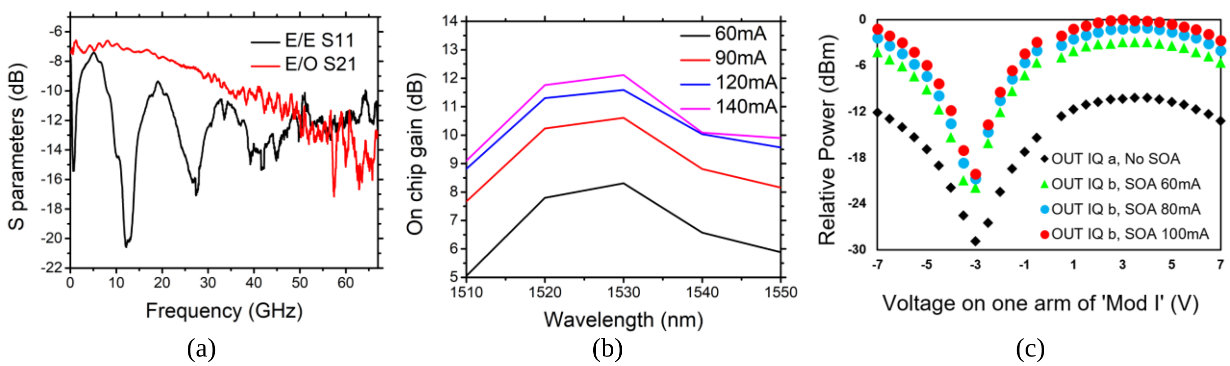


Fig. 2: (a) Measured S11 and S21 with 2.5V reverse bias applied to the top arm of the Mod I modulator. (b) SOA gain against wavelength, for several SOA driving currents. The optical power coupled in the SOA waveguide is -6 dBm. (c) Relative output power at the transmitter output, with and without SOA, laser wavelength = 1550nm, input laser power = 10 dBm.

### 4. SOA Characterization

The SOA has a 400µm-long active section, with a 5% mode confinement in the QW. The low confinement enabled by the hybrid waveguide is beneficial to reduce the saturation by ASE, and to improve the noise factor by allowing carrier density to be uniform along the device [6].

We first investigate the SOA optical bandwidth on a standalone SOA. Figure 2(b) gives its measured on-chip gain against the wavelength of the input laser with -6dBm of power at the input of the SOA waveguide. Such a power corresponds to the power seen by the SOA in an integrated transmitter configuration, fed by a +16dBm tunable laser (+16dBm – 20 to 25 dB IL). The -2 dB optical BW is ~35nm. The noise figure (NF) measured as the difference between the input and output OSNR ranges between 10.5 and 8.5dB.

We then characterize the amplification behaviour of the SOA within the integrated transmitter. The external laser is set at 1550nm and is coupled at the ‘IN IQ’ port. We compare the amplified and non-amplified signals respectively at the ports ‘OUT IQ b’ and ‘OUT IQ a’. ‘Mod Q’ is set at carrier suppression, while ‘Mod I’ is set at quadrature. The heater ‘HIQ’ is left unbiased as the phase between ‘Mod I’ and ‘Mod Q’ does not influence the following measurement. Figure 2(c) reports the power measured at the optical spectrum analyzer (OSA) at the signal wavelength (1550nm) for several SOA currents, as the PN voltage of one arm of ‘Mod I’ is varied.

A ~10 dB gain is obtained with a 100mA SOA driving current, consistent with the measurements of the standalone SOA at 1550nm reported in Figure 2(b). No significant change of gain is observed as the voltage applied on one arm of ‘Mod I’ extinguishes the light at the input of the SOA.

## 5. SOA behaviour OOK and PAM4 modulation

The quality of signals after an SOA is limited by SOA noises for low input powers, and by signal distortions due to gain saturation for large input powers. Saturation of the gain not only induces amplitude errors but also phase errors due to the coupling of the alpha factor [6]. Therefore, to investigate the suitability of our integrated SOA to boost the output signal of an IQ modulator, we further test the performance at large signal modulation of the integrated transmitter by driving the ‘Mod I’ with a $2^{15}$ -1 pseudorandom bit sequence (PRBS) and measuring the eye diagram using Direct Detection. ‘Mod I’ is set at quadrature. Its arms are biased at -2.5V and driven in a push pull configuration with 5.7V Peak-to-Peak Differential voltage. The modulated light is directly detected by a 40GHz photodetector and sampled by a Keysight DCAX-86100D. In this setup, no optical filter is used to reduce the ASE. The DCA applies a linear equalizer filter with four taps. The laser power input to port ‘IN IQ’ is set to 13dBm. ‘Mod I’ is set at quadrature and ‘Mod Q’ at carrier suppression. The eye diagram measurements at 40 GBaud are reported in Figure 3, with OOK and PAM4 signals. Table 1 summarizes the measured eye characteristics. The outer ER of the PAM4 eye pattern is measured by the ratio between the topmost level (level 3) and bottommost level (level 0). This shows that SOA amplification is achieved without distorting the waveform. The SNR and optical modulation amplitude (OMA) of low power signals are improved with high dynamic extinction ratio (ER).

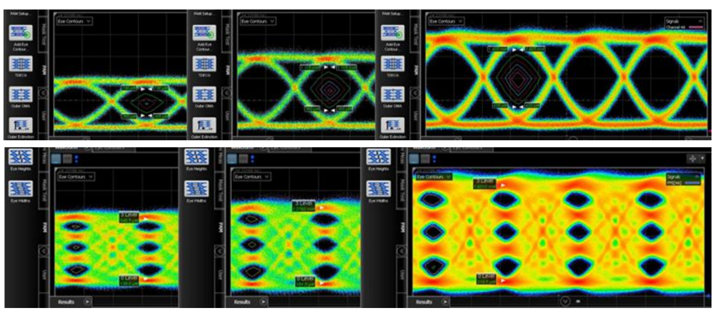

Fig.3: 40 GBaud eye diagrams at several SOA currents.
Top: OOK; left 60 mA, middle 80 mA, right 100 mA.
Bottom: PAM4; left 60 mA, middle 80 mA, right 100 mA

Table 1: 40 GBaud eye measured characteristics at several SOA currents

| SOA current (mA) | | 60 | 80 | 100 |
|---|---|---|---|---|
| OOK | OMA, µW | 806 | 1194 | 1505 |
| | Outer ER, dB | 8.7 | 8.9 | 9 |
| | SNR, dB | 8.1 | 9.4 | 9.8 |
| PAM4 | level 0, µW | 124 | 172 | 205 |
| | level 3, µW | 880 | 1287 | 1627 |
| | Outer ER, dB | 7.9 | 8.5 | 8.6 |

## 6. Conclusion and Future work

We demonstrated the integration of an Si IQ MZM with a III-V/Si SOA. The 100mA-driven SOA achieves a 10 dB gain at 40 GBaud with OOK and PAM4 modulations applied on one of the two nested MZMs. No waveform distortion is observed despite large amplitude modulation. We therefore anticipate no additional penalty for complex phase and amplitude modulations. Coherent transmission tests will be further performed on packaged circuits.

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