Contribution ID: **181**

Type: **Oral**

Compact Silicon Photonic Mach-Zehnder Modulators for High-Energy Physics

Friday 6 October 2023 10:30 (20 minutes)

The characterization of compact non-traveling-wave Mach-Zehnder modulators (NTW-MZMs) for optical readout in high-energy physics experiments will be presented to provide power-efficient alternatives to conventional traveling-wave devices and a more resilient operation compared to ring modulators. Electro-optical small-signal and large-signal measurements will be reported to show the performances of a custom NTW-MZM designed and fabricated in iSiPP50G IMEC's technology in the framework of INFN's FALAPHEL project. Bit-error-rate results will demonstrate its potential suitability for data links up to 25 Gb/s when being driven by voltage levels compatible with integrated CMOS drivers.

Summary (500 words)

Novel radiation-tolerant optical links are required to handle the foreseen growth of data volumes and radiation intensities in the innermost regions of future detectors (e.g., HL-LHC, FCC, etc.). Limitations in the radiation hardness of current readout optoelectronic modules (e.g., lpGBT) have led to research activities regarding the suitability for using silicon photonics (SiPh) in high energy physics (HEP) experiments. Recent works have already reported SiPh active devices (e.g., high-speed depletion-driven PN-junction phase shifters, photodetectors, etc.) with reasonable radiation-tolerant behavior with the application of proper design hardening techniques or annealing procedures [1,2]. Although being still under deeper evaluation, this promising radiation resistance is now driving the development of fully-integrated SiPh-based transceivers (TRXs) to provide next-generation HEP readout systems [3].
In this context, the selection of electro-optical modulating devices becomes critical in addressing system-level requirements. Standard foundry-process SiPh technologies typically allow to implement free-carrier-based Mach-Zehnder (MZMs) or ring modulators (RMs). While RMs offer compact sizes, low-power high-speed operation and straightforward wavelength division multiplexing (WDM), their resonance is highly sensitive to temperature and process fluctuations, and they often need power-intensive wavelength-locking mechanisms. On the other hand, MZMs are optically broadband and do not typically require strict stabilization against environmental changes. Nonetheless, they are often characterized by large footprints which impose careful radio-frequency (RF) traveling-wave (TW) design to efficiently apply modulation to optical waves. This translates in the need for on-chip RF termination resistors where both static and dynamic power dissipation take place and make TW-MZMs less power-efficient than RMs.
To provide a more compact and low-power interferometric modulator version to be used in HEP TRXs, we will report in this work the experimental characterization of a non-TW-MZM fabricated in iSiPP50G IMEC's technology within INFN's project FALAPHEL. Millimeter-scale phase shifters which usually compose TW-MZMs have been laid out in a meandered pattern to decrease the footprint but still retain a reasonable modulation depth. A 1.5 mm-long active phase shifting length has indeed been folded in a ~500µm x 500µm area considering all required bond-pads. To give a fair comparison, RM designs typically end up with ~400µm x 150µm footprint (including thermal heater contacts), while TW modulators more than ~500µm x 2mm.
The active optical length in a non-TW-MZM design is thus decoupled from the effective RF length, allowing to shift the onset of TW effects to higher RF frequencies. Probing the proposed MZM in a 50 Ω testing environment results in ~6.5 to ~8.5 GHz -3dB electro-optical bandwidth depending on bias voltage.
Non-return-to-zero (NRZ) transmission experiments have been conducted recording eye diagrams and bit-error-rate (BER) versus optical power at the photo-receiver. The latter measurements have been taken with a (quasi-)CMOS compatible voltage swing of 1.4 V showing that BER levels below the soft-decision forward

error correction (FEC) threshold are still achievable till 25 Gb/s. Instead, almost error-free transmissions have been captured till 35 Gb/s with 4.5 V peak-to-peak driving.

References
[1] M. Lalović et al., doi: 10.1109/TNS.2022.3148579
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[3] T. Prousalidi et al., doi: 10.1088/1748-0221/17/05/C05004

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Session Classification: Optoelectronics and Electrical Data Links

Track Classification: Optoelectronics and Electrical Data Links