Silicon Photonic Devices for Optical Data Readout in High-Energy Physics Detectors

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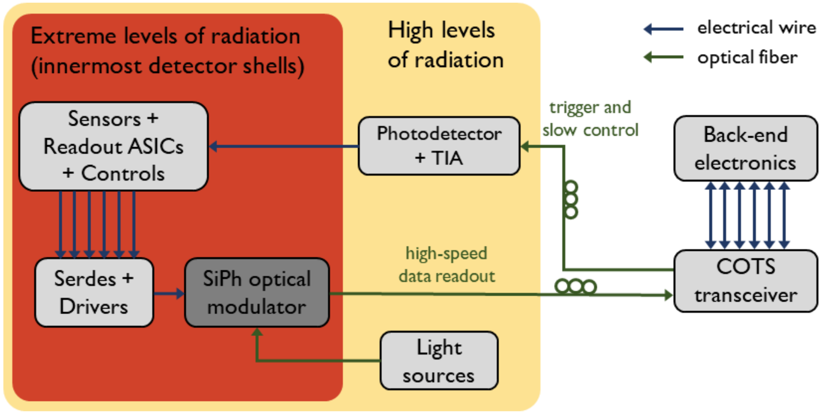
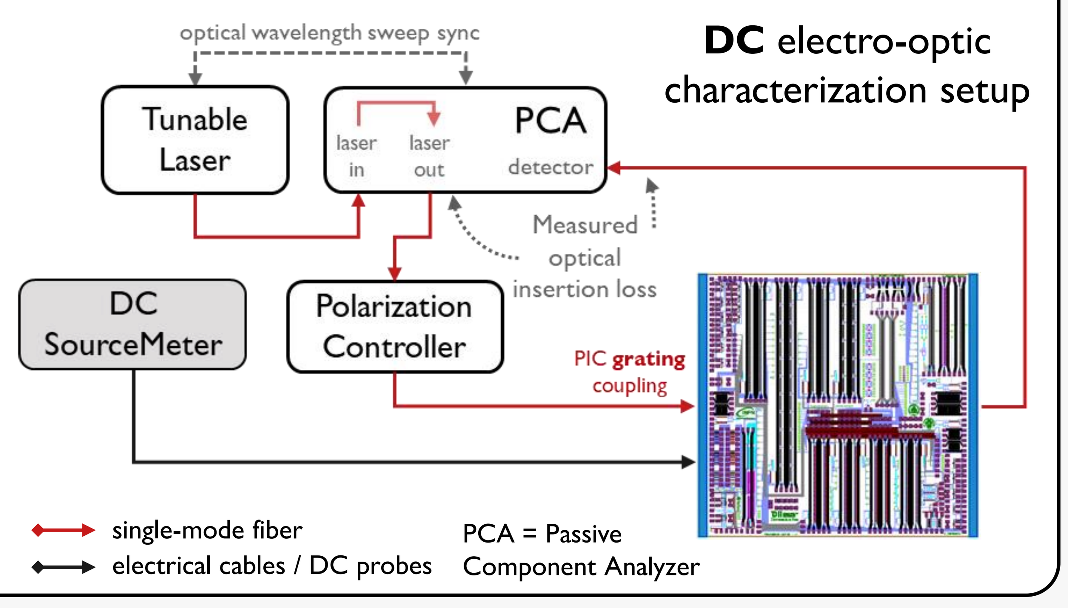
1. Introduction

- Next-generation high energy physics (HEP) detectors require radiation tolerances up to **10 MGy** of total ionizing dose (TID) and **> 5·10^{16} n/cm^2** 1 MeV-equivalent neutron fluence (NIEL). Directly-modulated lasers will no longer sustain such radiation levels.
- Properly-engineered silicon photonics (**SiPh**) devices are currently being qualified to provide *radiation-tolerant electro-optic transceivers*



2. Custom-designed photonic integrated circuit (PIC)

- Full-custom PIC in Imec's iSiPP50G technology designed to explore several electro-optical modulation possibilities (MZMs, RMs and EAMs)
- This work presents preliminary experimental characterizations of some SiPh modulators developed within the **FALAPHEL** project



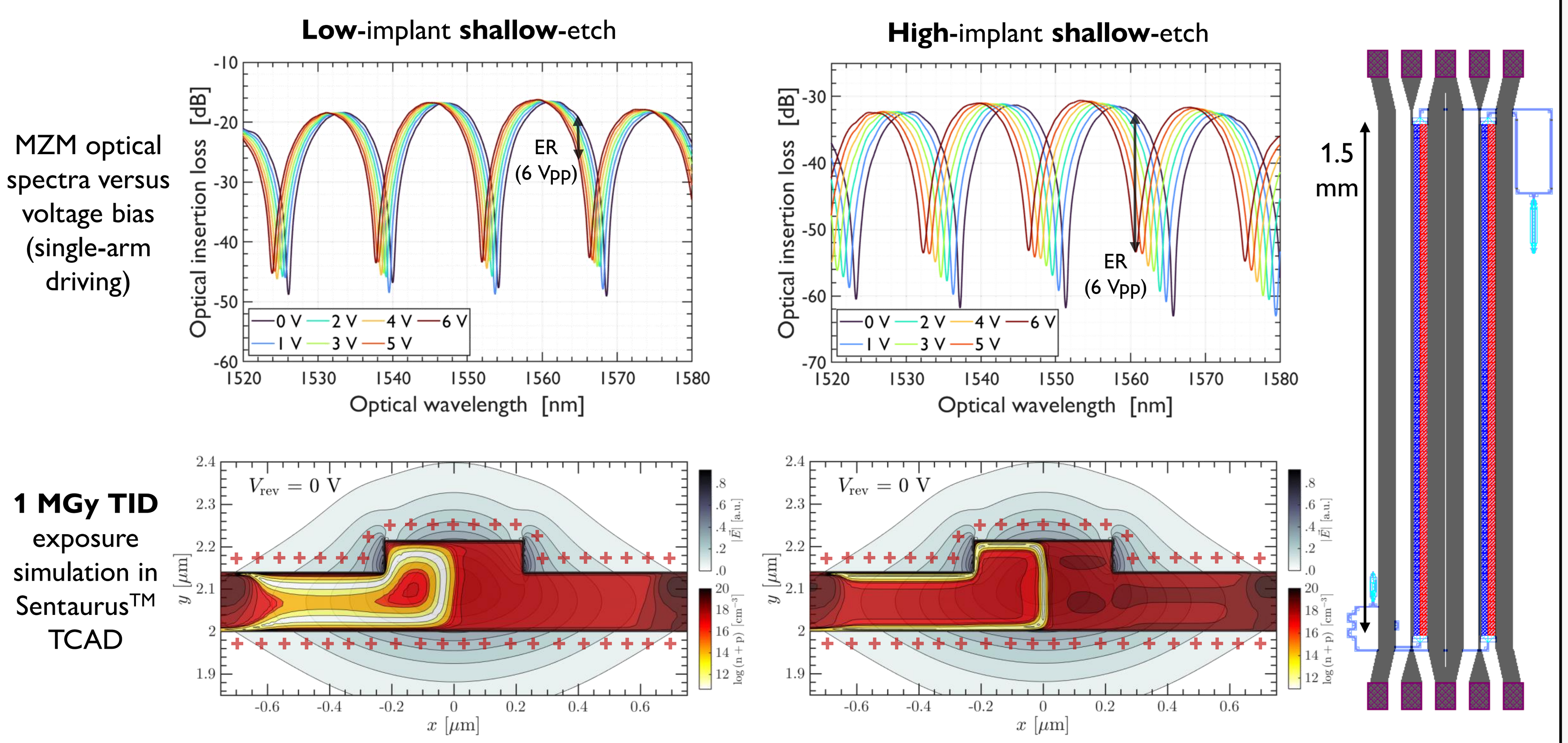
3. Silicon Photonic Mach-Zehnder Modulators (MZMs)

- Mach-Zehnder modulators (**MZMs**): phase modulation converted in amplitude modulation through interference. All-silicon phase shifting is achieved via plasma dispersion effect through *depletion-driven PN junctions embedded in rib waveguides*
- **Ionizing radiation** induces positive charge accumulation in oxide layers, determining a progressive pinch-off of the P-doped slab

Device-level radiation-hardening by design (**RHBD**) techniques

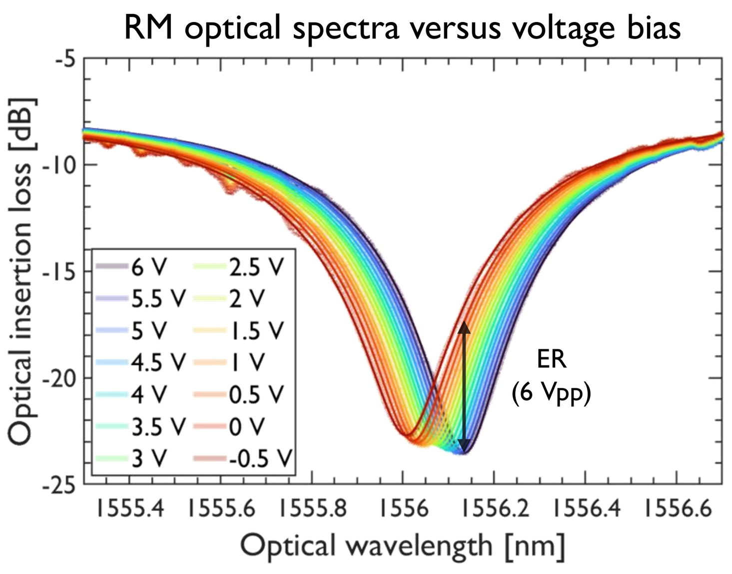
1. Shallow-etch rib waveguides
2. Doping concentrations increase
3. Periodic application of forward-bias

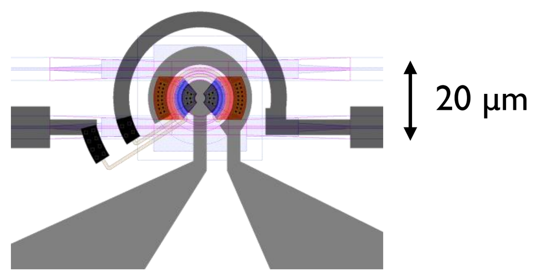
- Shallow-etch 1.5 mm-long MZMs have been designed both with low- and high-doping implants. They respectively present modulation efficiencies $V_\pi L_\pi$ of 1.2 V·cm and 2.6 V·cm with an insertion loss difference around 14 dB



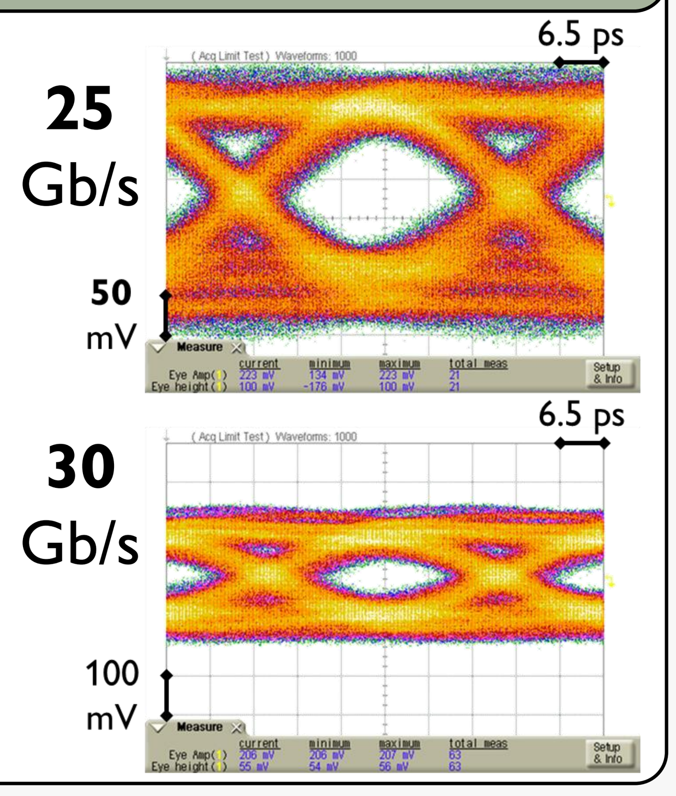
4. Silicon Photonic Ring Modulators (RMs)

- Ring modulators (**RMs**): light intensity modulation is achieved via resonance shifts produced with a PN phase shifter. RMs are more compact than MZMs but are extremely sensitive to temperature and fabrication fluctuations.
- Preliminary high-speed tests with RF probes validate the operability of the presented custom-designed RM up to 30 Gb/s with open eye diagrams. Testing conditions: λ = 1556.16 nm, V_{bias} = 1.7 V, V_{pp} ~ 4 V, T = 21.3 °C
- RHBD slab thickening not viable for small-bending radius (i.e., large free spectral range) configurations because of excessive radiative losses. RHBD techniques are almost limited to increases in doping concentrations



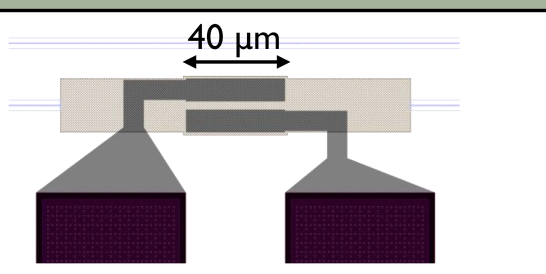


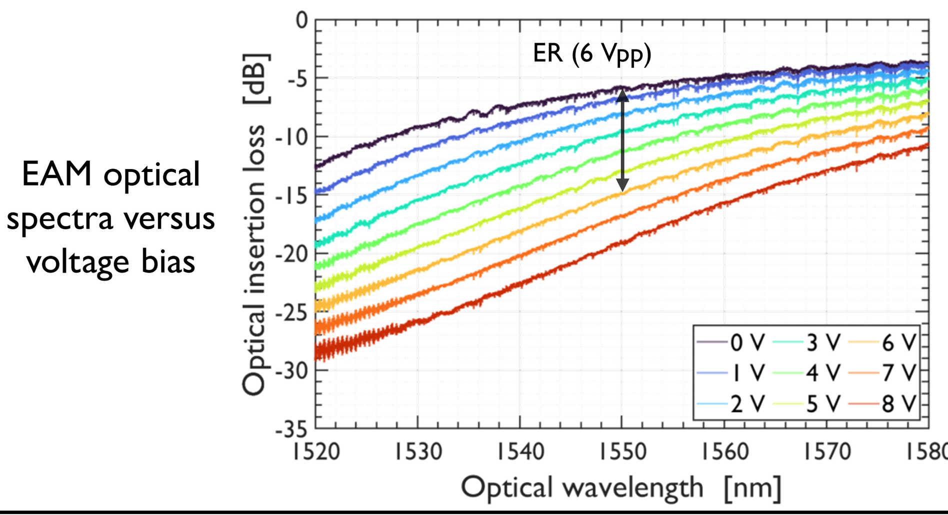
FWHM	~ 790 pm
Q	~ 2000
Modulation **depth**	~ 15 dB
Modulation **efficiency**	~ 25 pm/V

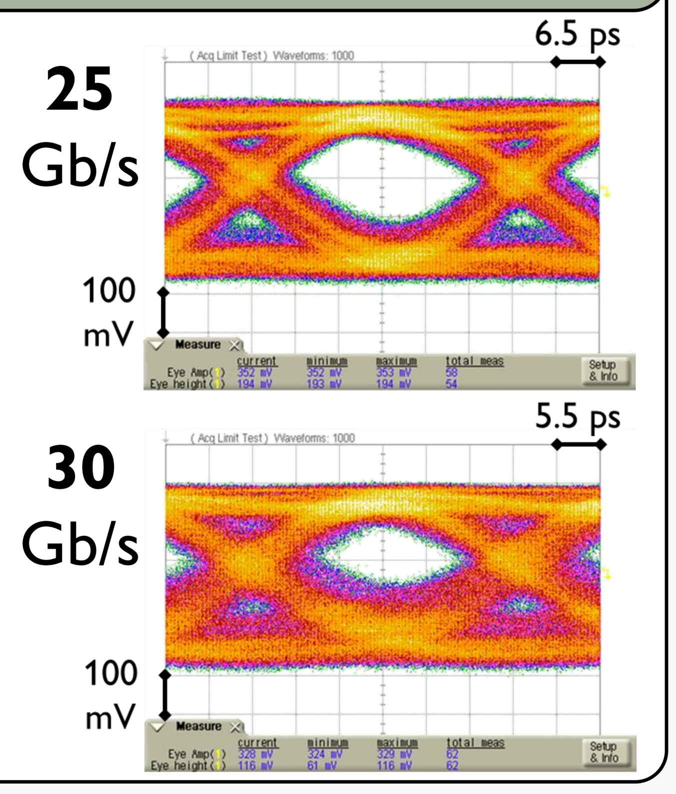


5. Silicon Germanium Electro Absorbtion Modulator (EAMs)

- Electro-absorption modulators (**EAMs**) are silicon-germanium (**SiGe**) devices where an electric field-dependent photon absorption is harnessed for light intensity modulation. A PN junction is placed inside the SiGe rib waveguide to modulate the electric-field in the material where optical power flows.
- The presented device (foundry building block) has been tested with RF probes and validated to work up to 30 Gb/s with open eye diagrams. Operating conditions: λ = 1550 nm, V_{bias} = 2.2 V, V_{pp} ~ 4 V, T = 21.3 °C
- SiGe EAMs radiation resistance is not properly documented yet, but previous irradiation results carried out at CERN on SiGe photo-detectors show promising performances both in terms of TID as well as displacement damage, foreseeing sufficient hardness also for EAMs.







6. Conclusions and Perspectives

- Each presented SiPh modulator paves the way to the development of rad-hard multi-Gb/s SiPh-based transceivers. Nevertheless, a complete characterization still needs to be performed and the next steps will be:

1. Irradiation campaigns to assess SiPh's radiation tolerance against X-rays, protons and heavy ions
2. Hybrid integration (on RF-PCB) of the presented RM with a custom-designed electronic driver (TSMC 28nm HPC tech)
3. Further high-speed and RF electro-optical characterization of the implemented SiPh modulators

7. Acknowledgements

Falaphel

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