Readout Technologies for Future Detectors

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RDC5 Meeting

Introduction

- We are interested in low-power readout technologies to allow tigerless data-taking (without on-detector buffering).
- **Radiation-tolerant fast data links** are required to answer the challenge. Some HEP experiments (e.g. DUNE) can also benefit from cryogenic-capable fast links.

- Therefore, we would like to continue working on radiation-tolerant Si-photonics optical interconnects.
- We are also interested in wireless data links, emerging computing architectures, neuromorphic on-detector data processing.

- Close partnership with industry is key to cost-effective adoption of these technology.
- However, selected elements need to be revised to work in radiation- or cryo- enviroment.
  - E.g. modulators and resonators in Si-photonics PDK.

Outlook

- Test of commercially-available optical links, wireless links, neuromorphic and other computing architectures.
- Identify commercial partners to bring these technologies to HEP
- System-wide evaluation of optical (WDM) vs electrical data aggregation.
- System-wide evaluation of on-detector data processing (edge AI/computing).
- Develop and evaluate key elements of the new technologies (e.g. rad-hard WDM and modulation).

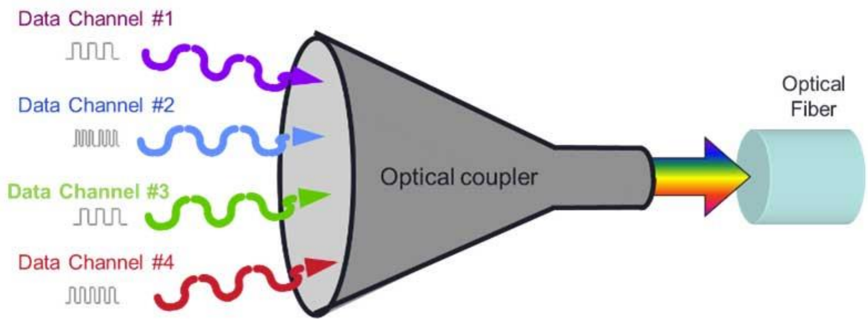
BACKUP

Future needs

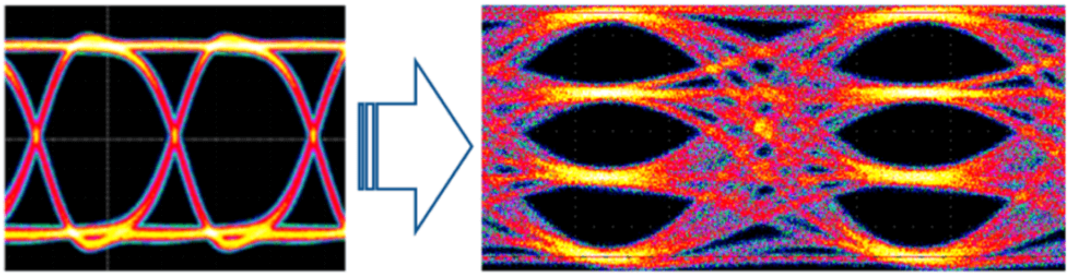
- An FCC-hh detector needs to output about 10 Pb/s.
  - Using Versatile Link + (10Gb/s) → ~1e6 fibers.
  - In comparison, ATLAS will uses ~1e4 fibers for the phase-2 upgrade.
- 80% of the FFC-hh bandwidth is from the tracker. Availability of rad-hard links can also make a huge difference.
- The 10 Gb/s is a bit below capabilities of the modern FPGA transceivers (25-112 Gb/s). We underutilize the I/O capabilities of FPGAs and that increases cost and size of the off-detector readout system.
  - Modern FPGA have transceivers capable of 112 Gb/s
  - Keeping the link speed at 10 Gb/s will also sky-rocket the cost of the off-detector components for FCC-hh
- It will be almost impossible to readout FCC-hh detectors without increasing speed and radiation tolerance of the data links. The link speed needs to increase at least 10 times.

Industry trends

- All the data links for 100m range are fiber-optical. We can not use copper cables because of the high power consumption.
- VCSEL-based 400 Gb/s QSFP transceivers operate at 50 Gb/s per fiber.
- Si-photonics offers 400 Gb/s QSFP modules operate at 100 Gb/s per fiber.
  - Si photonics offers slightly lower power consumption than VCSELs.
- WDM (wavelength division multiplexing) reduces the number of fibers



- PAM (pulse amplitude modulation) instead of NRZ (non-return to zero)



NRZ PAM4

R&D

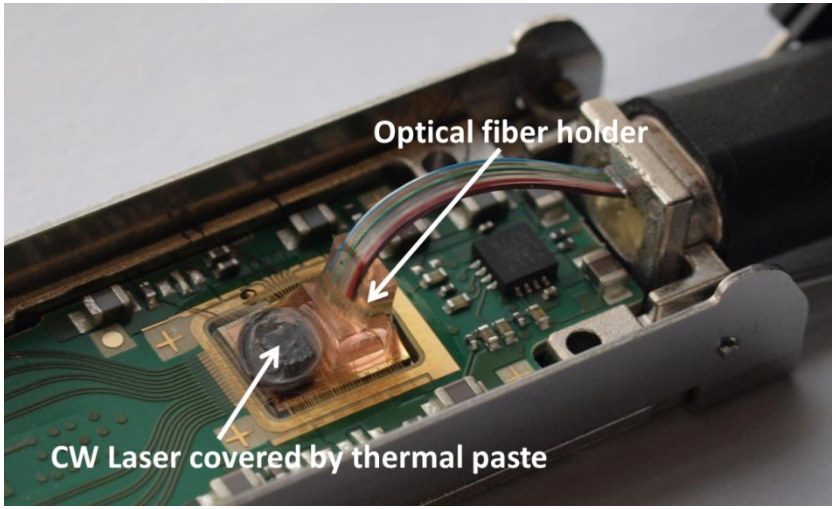
- Alas, industry does not need rad-hard or cryo-capable data links.
- So far we have been using VCSEL-base links (e.g. VL+) and Si-photonic links are in development.
- Wireless data transmission is also interesting. It allows broadcasting for control and configuration of detectors and does not need bulky copper cables.
- The off-detector systems are likely to continue using FPGAs since the on-detector electronics is synchronous to the beam and custom data transmission protocols are used to control the detectors.
- However, the connectivity between the FPGAs and commodity computing will need to go beyond PCIe gen5 (or TCP/IP).
  - There are CPU-FPGA hybrids but it is not clear if we can use them for detector readout. The serial links are not customizable and we also need to supply user-defined clock signals.
- The majority of the design effort is spent on testing and verification of FPGA firmware. Complexity of the future detectors is likely to be higher. Novel design approaches may significantly reduce the effort.

Rad-hard optical links

- R&D for rad-hard VCSEL-based and Si-photonic links is ongoing.
- VCSELs is still the mainstream technology.
- The HEP community can not develop VCSELs for radiation tolerance so we select commercial products most suitable for our needs.
- For VCSELs we develop rad-tolerant drivers and circuits for reading out the photo-diodes.
- Si-photonic transceivers are fully customizable for rad-tolerance. However, we do not have a lot of expertize in the community.
- For the VCSEL-based links the data aggregation is typically done logically (a data frame is assembled of smaller pieces). This is done by an on-detector IC (e.g. GBTx or lpGBTx).
- Si-pho links can also use native optical data aggregation via WDM.

Si-photonics links

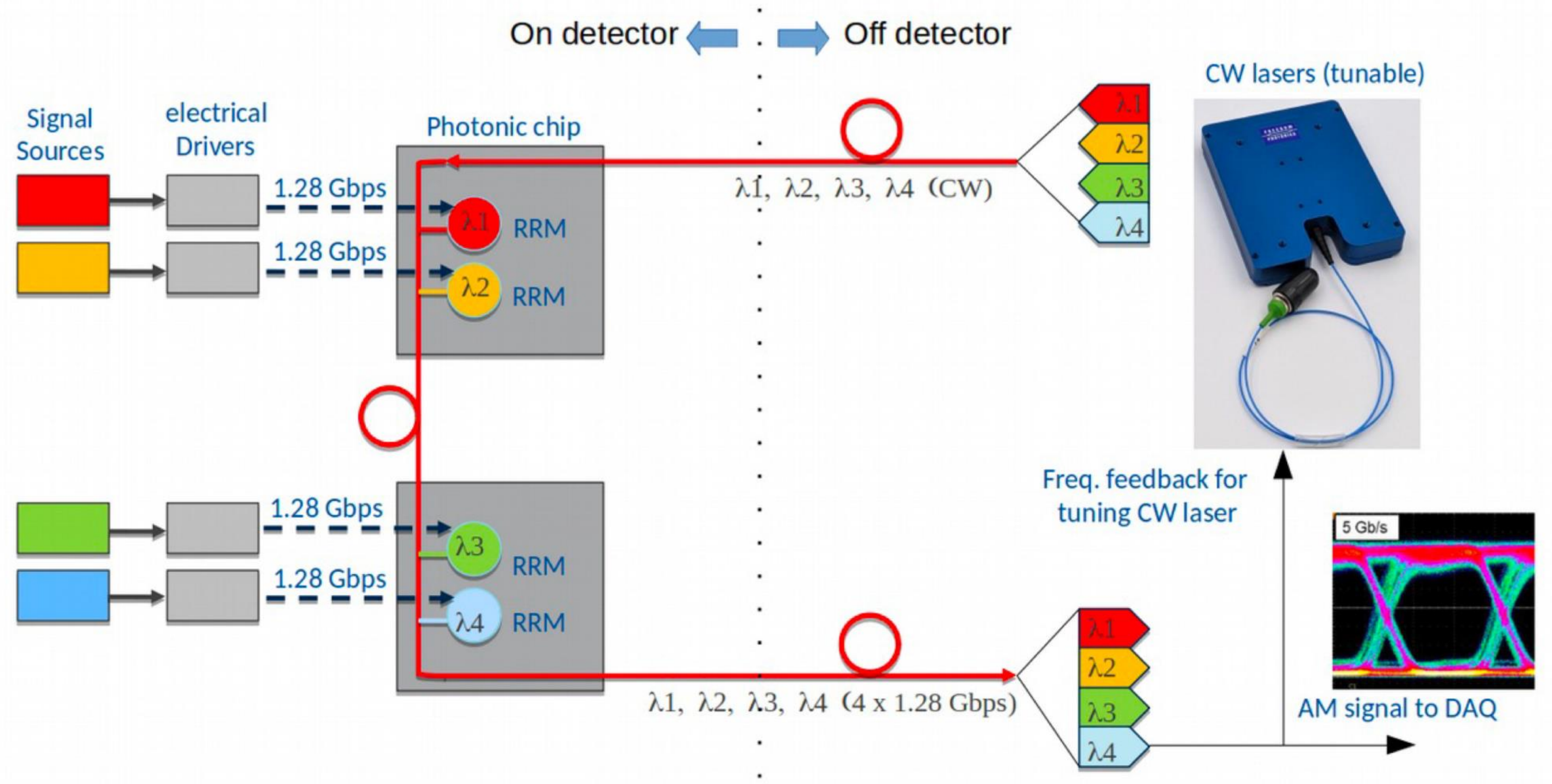
- Argonne has characterized radiation tolerance of commercial Si-photonics optical transceivers for the ATLAS experiment at the LHC. Other institutions (e.g. CERN) have also looked at the technology.
  - The optical components were found to be highly radiation tolerant.
- Target: TID~ 3 Mrad, NIEL~ 1e17 n/cm^2.



- The Si-photonics approach allows fabrication high-speed, low-cost, low-power, high-reliability, and low-BER fiber-optical transceivers
- Si-photonics utilizes fabrication of optical circuits in the same wafer as electrical circuits using conventional CMOS processes. →"Fiber to chip" instead of copper cable
- E.G. The technology could significantly reduce the mass, complexity, and power consumption of the FCC-hh inner tracker while also improving its performance.
- The HEP community could benefit from further adopting the technology through partnership with commercial companies or by developing our own devices and expertise. The Si-phonics device libraries are widely available.

Rad-hard Si-pho WDM link

- SBIR with Freedom photonics.
- Data aggregation and modulation happens on the same wafer. One fiber in and one fiber out. Ring resonators have small footprint.

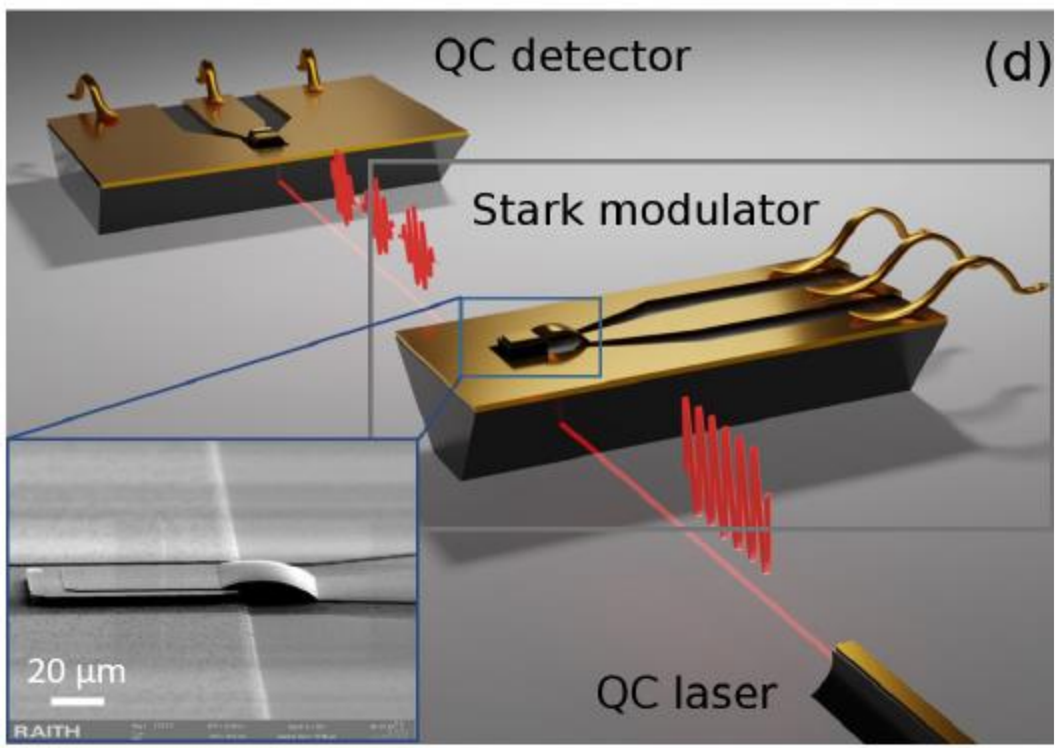


Wireless Microwave Technology

- Data rates of several Gb/s.
- 60 GHz band
- 1x1 cm antenna and 2.5x2.5 mm IC.
- Lowe power consumption (<0.3W)
- Error rate at 4 Gb/s over 1m distance is 1e-11.
- The cross-talk is reduced because the signal does not penetrate the tracker sensors.

Free-space optics

- 2.5 Gb/s over 2m at 1e-12 BER.
- mid-IR wavelength



Si photonics technology uses a commercial CMOS SOI process (see 10.1109/JSSC.2007.908713 or 10.1109/OFC.2008.4528356). The optical elements are:

- Passive waveguides (losses<0.1 dB/cm) → interconnects between other optical devices.
  - Utilize the high index of refraction between Si and SiO_2.
- Phase modulators → Used in the MZI-based amplitude modulators
  - The refractive index of Si depends on the free carrier density (electrons and holes)
  - Implemented as a PN diode structure by using implants
  - Bias the PN diode to change the phase
- High-speed photo detectors
  - Selective growth of Ge on top of the Si waveguide.
- Low-loss grating couplers, holographic lens (efficiency ~ 95%)
  - Used to couple light in and out of the Si die
  - Redirect light from horizontal direction (die) to vertical (fiber)

From D. Kucharski, Hot Chips 21, Aug. 24, 2009