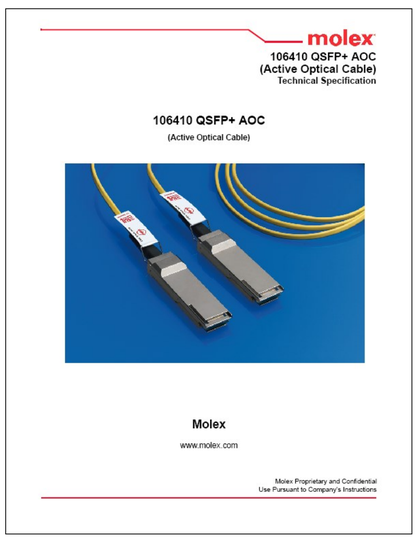
A New High-Speed Optical Transceiver For Data Transmission at the LHC Experiments

A. Paramonov, G. Drake, R. Stanek, D. Underwood
Argonne National Laboratory, Lemont, Illinois 60439, USA

Fiber-optic links from Molex



We consider an off-the-shelf optical transceiver as a candidate for high-speed fiber-optic links for the Tile (hadronic) calorimeter of the ATLAS experiment. The device modulates light from a continuous wavelength (CW) laser using Mach-Zehnder interferometers (MZI).

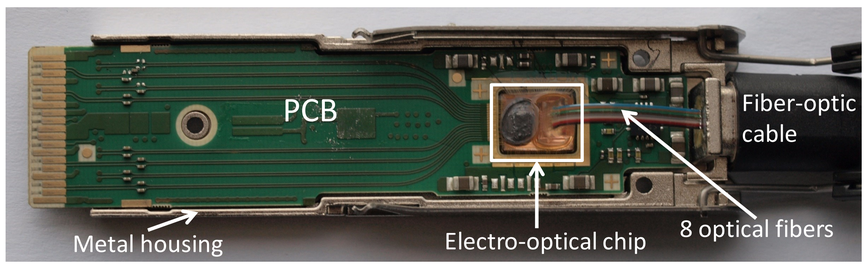
- High Bandwidth
  - 4 bi-directional channels: 1-14 Gbps each
  - Scalable to higher speeds and number of channels (future devices)
- Low Bit-Error Rate (BER)
  - BER<10^{-18} (tested by Luxtera: no bit errors were observed)
- Long Wavelength
  - Uses cheap single-mode (SM) fiber for long-range and high-speed communications
- High reliability
  - Industry-standard QSFP package (cooling and mechanical)
  - CW DFB laser
  - MZI (modulators) → No known failure mechanisms; MTBF > 2.3 x 10^9 hrs (300M device-hours without a failure)
- Low power consumption
  - <780 mW for a 4-channel transceiver (one end)
- Low cost
  - ~$250 per device
  - CMOS is a low-cost platform for optical devices

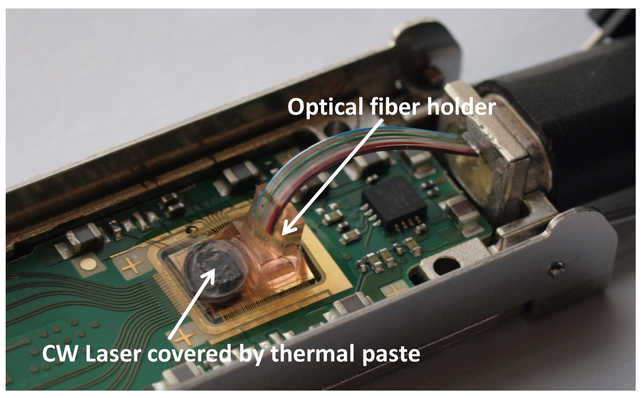
The device meets all the electrical and mechanical requirements. We only need to evaluate its radiation tolerance.

Inside the QSFP module assembly

Main components of a QSFP module assembly:

- Electro-optical chip
- Printed circuit board
- Fiber-optic cable
- Metal housing





The electro-optical chip, heart of the transceiver, is built using the silicon photonics technology platform developed by Luxtera.

Almost all functionality of the device is implemented in the electro-optical chip. The packaging of the device is very clever:

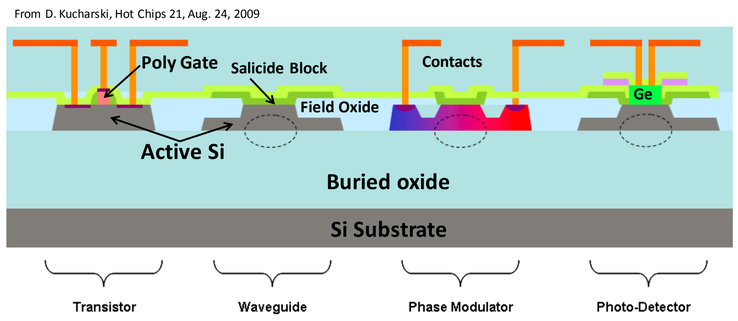
- The die is wire-bonded directly to the PCB
- The single CW laser (1490 nm) is directly coupled to the die
  - Passively aligned
  - Covered in thermal paste
  - The metal housing acts as a heat sink
- The 8 optical fibers (4 in & 4 out) are also coupled directly to the die
  - A holder is used
  - Passively aligned

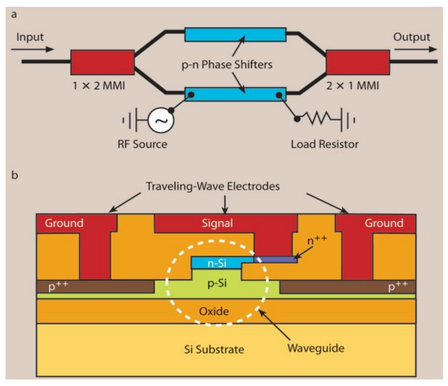
Inside the electro-optical chip: silicon photonics

Si photonics allows to manufacture electrical transistors and optical devices in the same die. The technology uses a commercial 130 nm 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



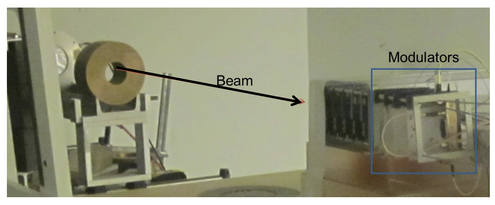


From http://www.photonics.com/Article.aspx?AID=29078

Irradiation results: Overview

CMOS circuits can be designed to be radiation hard. Therefore, we are mostly interested in radiation hardness of the optical elements (waveguides, MZIs, photo-detectors, etc). We characterize the transceiver for different radiation effects using beams of:

- Gamma-rays from a Co^{60} source
  - Total Ionizing Dose (TID)
  - Holes trapped in the gate oxides layer degrade performance of MOSFET transistors
- Fast neutrons
  - Displace atoms. Create defects in the lattice.
  - **No issues up to 1.5x10^{12} 1 MeV-eq neutron/cm^2**
- Fast protons (200 MeV)
  - Localized ionization can cause single-event effects (SEE)
  - **No SEE @ 10^{12} protons/cm^2**



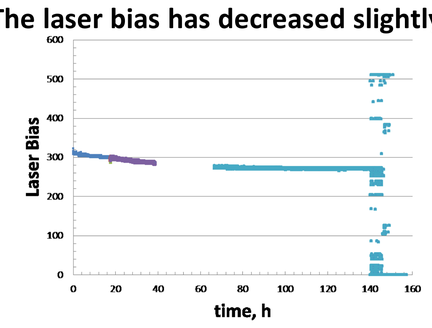
We monitor performance of the transceiver during the irradiation process by recording:

- Bit-Error Rate
  - Pseudo-random bit stream (PRBS7) is sent from an irradiated transceiver into fibers at 4x10 Gbps
- Laser bias voltage
  - Adjusted by the transceiver chip to keep constant light output from the MZIs
- MZI phase corrections
  - Adjusted by the chip for maximum extinction ratio
- Digital control interface
  - I^2C errors

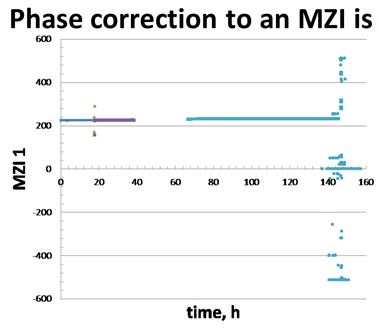
Irradiation results: Total Ionizing Dose

Irradiated two devices at ~ 2-2.5 krad/hour using a Co^{60} source. Ambient temperature and the supplied voltage were constant. The device was sending data after failure of I^2C.

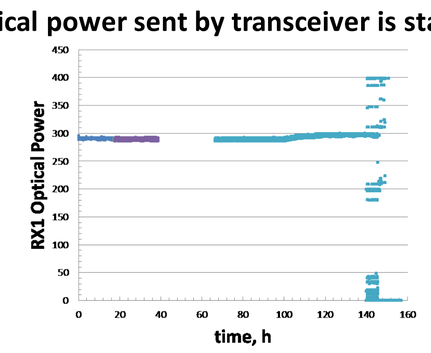
The laser bias has decreased slightly.



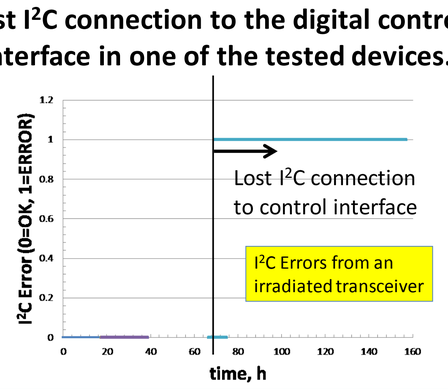
Phase correction to an MZI is stable.



Optical power sent by transceiver is stable.



Lost I^2C connection to the digital control interface in one of the tested devices.



Conclusions and outlook

CMOS photonics is an attractive platform for development of ultrafast fiber-optic links. It is a real competitor to VCSELs and InP-based modulators for long-range links.

- Low power consumption
- High integration density
- Low-cost
- High reliability
- The cheap SM fiber is scalable to THz speeds.

The irradiation tests suggest good radiation tolerance of the optical elements.

- The device is suitable for the radiation environment of the Tile calorimeter in the ATLAS detector (TID ~ 100 krad).
- The tolerance of the chip is limited by its digital control interface at TID ~ 170 krad.

The tested device was introduced to the market about 5-6 years ago. The next generation of CMOS photonics products can offer much more. There are promising improvements to higher speeds per fiber (>25 Gbps), more channels per die, multiple channels per fiber via wave-division multiplexing, and even better power consumption (see arXiv:1203.0767, 10.1109/JSSC.2007.908713, 10.1109/ECOC.2010.5621548, and 10.1109/ECOC.2008.4729209).

Argonne NATIONAL LABORATORY molex LUXTERA U.S. DEPARTMENT OF ENERGY

Argonne National Laboratory is a U.S. Department of Energy laboratory managed by U Chicago Argonne, LLC.