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

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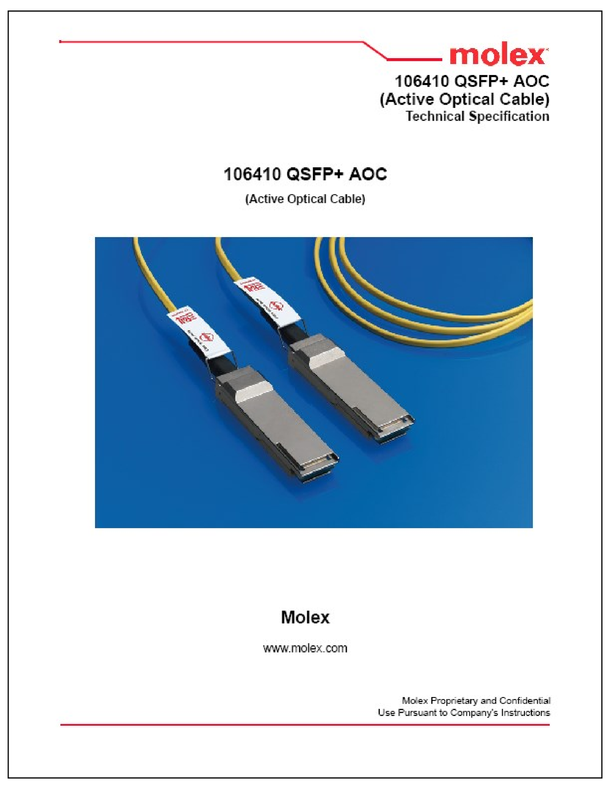
Fiber-optic links from Molex



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

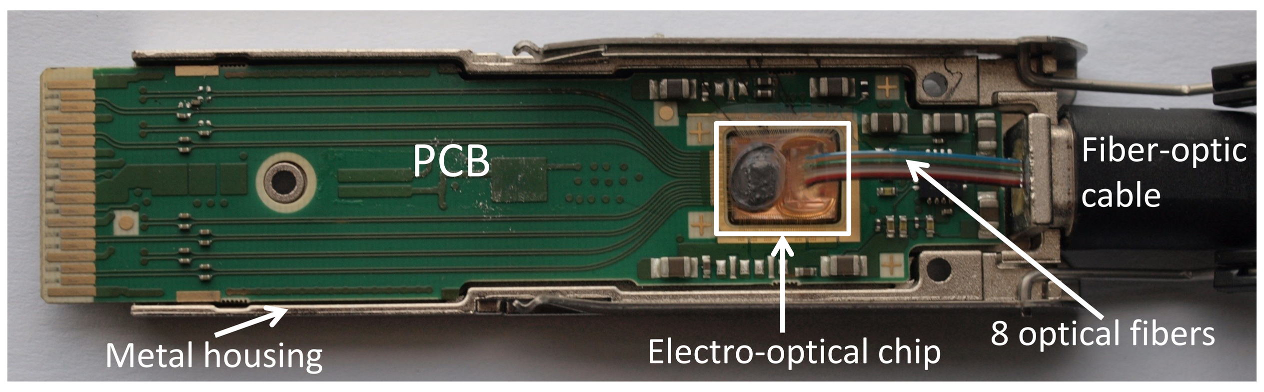
We consider an off-the-shelf optical transceiver as a candidate for high-speed fiber-optic links for the Tile (hadronic) calorimeter of the ATLAS experiment. The device modulates light from a continuous wavelength (CW) laser using Mach-Zehnder interferometers (MZI).

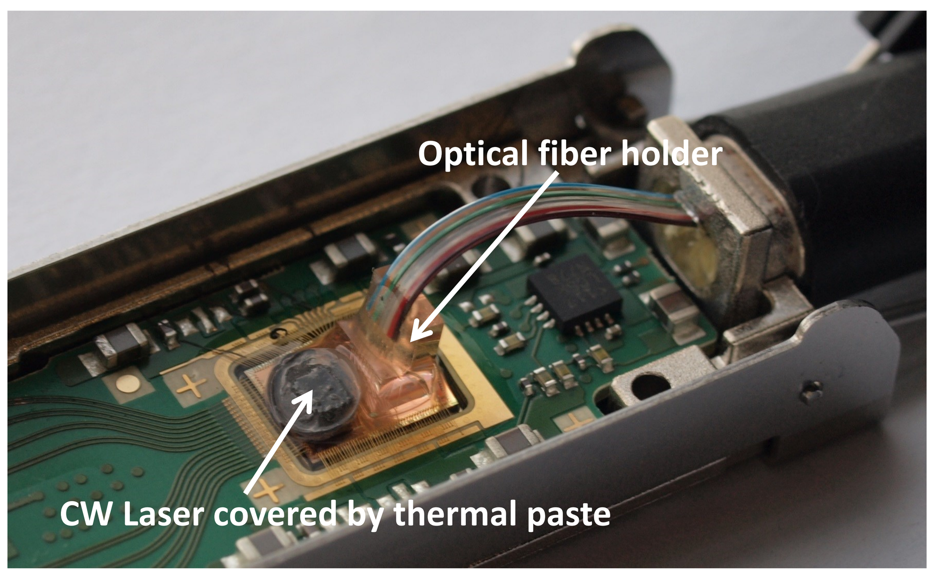
- High Bandwidth
  - 4 bi-directional channels: 1-14 Gbps each
  - Scalable to higher speeds and number of channels (future devices)
- Low Bit-Error Rate (BER)
  - BER<10^{-18} (tested by Luxtera: no bit errors were observed)
- Long Wavelength
  - Uses cheap single-mode (SM) fiber for long-range and 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

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:

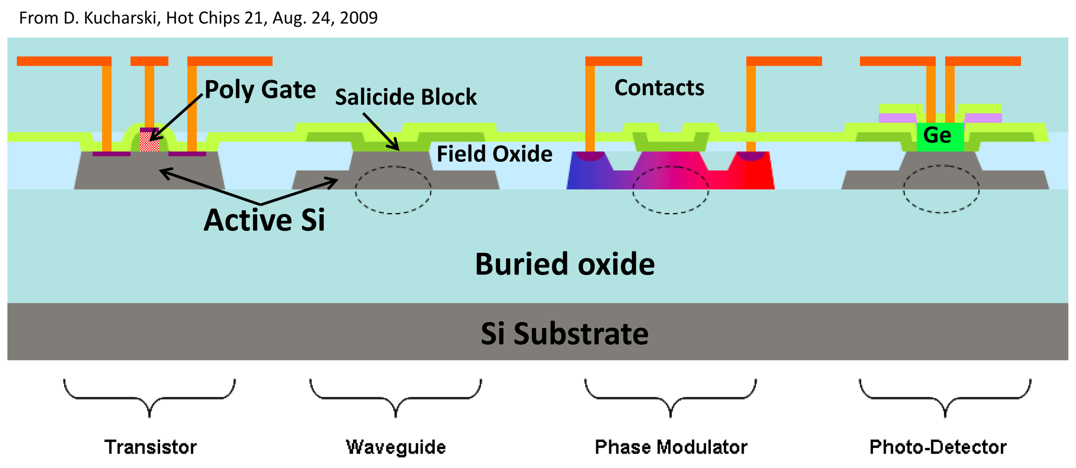
- The die is wire-bonded directly to the PCB
- The single CW laser (1490 nm) is directly coupled to the die
  - Passively aligned
  - Covered in thermal paste
  - The metal housing acts as a heat sink
- The 8 optical fibers (4 in & 4 out) are also coupled directly to the die
  - A holder is used
  -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

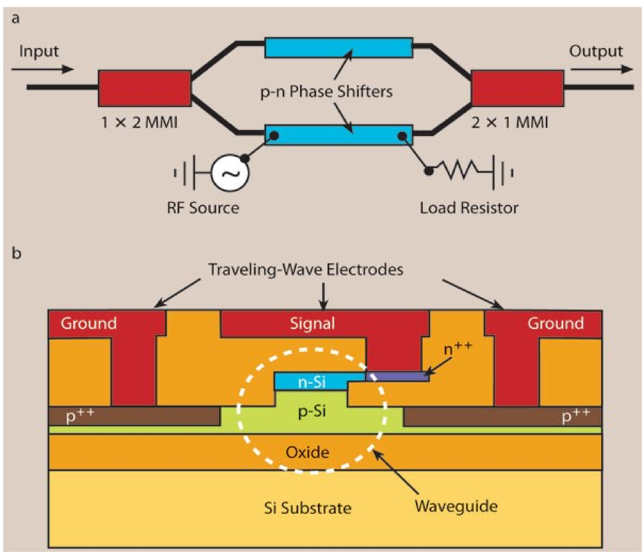
Inside the electro-optical chip: silicon photonics

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



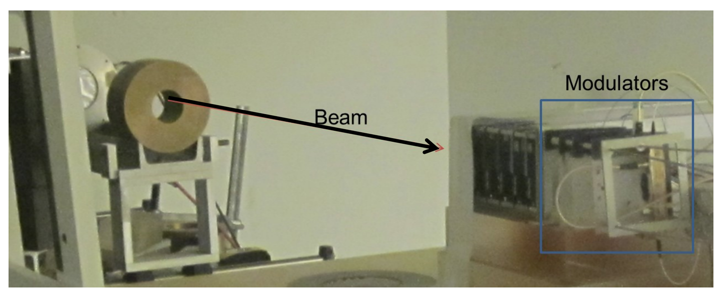


From http://www.photonics.com/Article.aspx?AID=29078

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 from beams of:

- Gamma-rays from a Co^{60} source
  - Total ionizing dose (TID) > 170 krad. Limited by the slow-control interface of the electro-optical chip.
  - Holes trapped in the gate oxides layer degrade performance of MOSFET transistors
- Fast neutrons (reactor)
  - **The laser is expected to be sensitive to NIEL.**
  - Displace atoms. Create defects in the lattice.
- Fast protons (200 MeV)
  - Localized ionization can cause single-event effects (SEE)
  - **No SEE @ 10^{12} protons/cm² => Will repeat the test.**



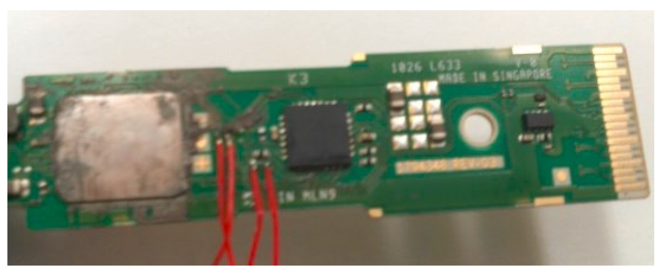
We monitor performance of the transceiver during the irradiation process by recording:

- 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
  - I²C errors

Integration into ATLAS' hadronic (Tile) calorimeter

The electro-optical chip is initialized by a micro-controller. It is a part of the QSFP module. The micro-controller has limited radiation tolerance (TID<20 krad). We are selecting a radiation-tolerant FPGA to replace the microcontroller (firmware is ready):

- MX-series (A42MX09) Microsemi
  - Antifuse-based FPGA
  - Package: PLCC84 → Does not fit inside QSFP
  - Process: 450 nm CMOS
  - Price: ~$60 per chip
  - Sensitivity to radiation: Antifuses are not affected by radiation. The tolerance is unknown.



- IGLOO nano (AGLN010, AGLN020, and AGLN060) Microsemi
  - Flash-based FPGA's
  - Packages: UC36, QN48, QN68, UC81, CS81 → Do fit inside QSFP
  - Process: 130 nm CMOS
  - Price: $1-$8 per chip
  - Sensitivity to radiation: FLASH can be erased by radiation. They observed a 10% increase of the propagation delay at TID of 22 krad (Si) for 350 MHz clock. We will operate the chip at 400 kHz. Therefore, we expect better radiation tolerance than that. Single event effects (SEE) can be mitigated with TMR.
  - Radiation tests are reported in http://www.microsemi.com/document-portal/doc_download/131375-radiation-tolerant-proasic3-single-event-latch-up-test-report and http://www.microsemi.com/document-portal/doc_download/131374-radiation-tolerant-proasic3-fpgas-radiation-effects-report

Conclusions and outlook

CMOS photonics is an attractive platform for development of ultrafast fiber-optic links. It is an alternative to VCSEL- and InP-based modulators for long-range links and offers:

- 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

Future plans:

- Radiation tests of QSFP modules where microcontrollers are replaced with FPGAs
  - Exposure to reactor neutrons
  - Re-evaluation of SEE's using energetic protons
  - TID of the FPGA's
- Annealing at high temperature (T=100 °C), single lot procurement

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