Free Space Optical Data Links

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Our Original Motivation

ATLAS/CMS: from design to reality
Amount of material in ATLAS and CMS inner trackers

- Active sensors and mechanics ~ 10% of material budget
- 70 kW power into tracker and to remove similar amount of heat
  - Very distributed heat sources and power-hungry electronics inside volume
  - Complex layout of services, most of which were not at all understood at the time of the TDRs
Technologies

- In the long run, Optics will be used for everything because of bandwidth.
- In the long run, modulators will be used instead of modulated lasers (e.g. VCSELs) because of Bandwidth (no chirp), Low Power, and Reliability.
- There are known Rad-Hard Modulators.
  - LiNO3 is in common usage, and has been tested for radiation hardness by several HEP groups. The only disadvantage for LiNO3 is size, (few cm long)
  - The IBM Mach-Zehnder in Silicon and the MIT absorption modulator in Silicon/ Germanium should be rad hard. We have tested the Si/Ge material in an electron beam at Argonne. These small modulators can in principle be integrated into CMOS chips.
- Many systems working at >~ 10 Gb/s already use modulators and CW lasers.
- Modulators enable one to get the lasers out of tracking.
Schematic view of use of Modulators and Light Beams in a High Energy Colliding Beam Tracking Detector

One concept

12 Tracking Cylinders, 10^7 Pixels, 1000 Optical paths (down from 40000 fibers in existing CMS detector)
Concept of communication between ID layers for trigger decisions

- A major improvement beyond even the conventional form of optical links could be made by using optical modulators so that the lasers are not in the tracking volume.
TECHNOLOGIES
Technology: Modulators

Modulators vs VCSELs

- **Advantages:**
  - **High bandwidth:** no chirp, no wires from detectors → commercial systems work >10 Gb/s/channel
  - **Low material budget:** Less Power inside detector → fewer wires needed → less cooling needed
  - **Higher reliability:** Laser sources outside the detector, modulators can be integrated into a single die, don’t need separate high current drivers, No high current density devices (VCSEL), less radiation/ESD sensitivity
Technology: Absorption Modulators

MIT Design of GeSi EAM Device Structure

- Fabricated with 180 nm CMOS technology
- Small footprint (30 µm²)
- Extinction ratio: 11 dB @ 1536 nm; 8 dB at 1550 nm
- Operation spectrum range 1539-1553 nm (half of the C-band)
- Ultra-low energy consumption (50 fJ/bit, or 50 µW at 1Gb/s)
- GHz bandwidth
- 3V p-p AC, 6 V bias
- Same process used to make a photodetector

Technology: Mach-Zehnder Modulators

Ultra-compact, low RF power, 10 Gb/s silicon Mach-Zehnder modulator

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Abstract: Silicon p⁺-i-n⁺ diode Mach-Zehnder electrooptic modulators having an ultra-compact length of 100 to 200 μm are presented. These devices exhibit high modulation efficiency, with a Vπ·L figure of merit of 0.36 V-mm. Optical modulation at data rates up to 10 Gb/s is demonstrated with low RF power consumption of only 5 pJ/bit.
Advances are Needed in Modulators for use in HEP

- We presently use LiNO3 modulators – fast, rad hard, but not small
- MIT and IBM have prototypes of modulators to be made inside CMOS chips
- It would cost us several $100k for 2 foundry runs to make these for ourselves
- There are commercial modulators of small size, but some are polymer (not rad hard) and some are too expensive at the present time
- We may have found a vendor (Jenoptik) for small Modulators who will work with us on ones which can be wire-bonded and have single-mode fiber connections
  - Need to test for radiation hardness of these

Active device
Approx. 1 Gram
Technicality: Free Space Data Links

- Advantages:
  - Low Mass
  - No fiber routing (c.f. CMS 40K fibers to route)
  - Low latency (No velocity factor)
  - Low delay drift (No thermal effects such as in fibers)
  - Work over distances from few mm (internal triggers) to ~Km (counting house) or far (to satellite orbit)
Technology: MEMS Mirrors

A commercially available MEMS mirror (Developed at ARI, Berkeley)

The Lucent Lambda Router:

Figure 4. Two images of MEMS-based OXC mirrors used in the Lucent LambdaRouter. The image in the upper right is a single mirror, and an array of mirrors is shown in the lower left. An eye of a needle is shown for comparison on the array.
Technology: Argonne MEMS Mirrors

- Argonne Center for NanoScale Materials, CNM, has designed and simulated novel MEMS mirrors that should solve the problems of commercial mirrors.
- The mirror is supported laterally and it can be actuated using 4 torsional actuators located in the vicinity.
- More stable mirror with better mechanical noise rejection.
- Under fabrication and we expect to have them available for testing very soon.

The figures show a 3D finite element analysis of the MEMS designed. The left panel shows the top view of the mirror and the right panel a bottom view.
ANL Concept of Direct Feedback to Establish and Maintain Stable Alignment
The commercial MEMS mirrors have ~40 dB resonance peaks at 1 and 3 KHz.

To use the direct feedback, developed an inverse Chebyshev filter which has a notch at 1 kHz, and appropriate phase characteristics (Left Figure).

With the filter we were able to make the beam follow a reflecting lens target within about 10 μm when the target moved about 1 mm (Right Figure).

Still has some fundamental issues at large excursion (~1 cm)

A separate feedback link solves this issue.

The amplitude-frequency map of our analog feedback loop, demonstrating phase stability at 100 Hz.

A test setup used to demonstrate MEMS mirror steering with an analog control loop which compensates for the mirror resonances at 1 and 3 KHz.
Due to diffraction, there is an optimum diameter for a beam for a given distance in order to reduce $1/r^2$ losses.

- The Rayleigh distance acts much like Beta-Star in accelerators
  - Relates waist size and divergence
  - Depends on wavelength

- If we start with a diameter too small for the distance of interest, the beam will diverge, and will become $1/r^2$ at the receiver, and we will have large losses (We can still focus what we get to a small device like an APD or PIN diode). This is typical of space, Satellite, etc. applications.

- If we start with an optimum diameter, the waist can be near the receiver, and we can capture almost all the light and focus it to a small spot

- Examples, ~ 1 mm for 1 m, ~ 50 mm for 1 Km
- Short/long distance
- Extreme low mass
- Very high speed
- Radiation hardness
- Reliability

Technology

- LiNO3 Modulators + fibers
- Mach-Zehnder Modulators + fibers
- Same die Mach-Zehnder Modulators + fibers
- Modulators + free space links for short distances
- Modulators + free space links for long distances
- Modulators + free space links + trigger
Applications

SHORT DISTANCES
Our Current Version

- **CW LASER** at 1550 nm
  - Optical -> Electric
  - ADC, TIA, DAC
  - SPI
  - Si Detectors
  - Rigid Coupling
  - Reflective lens
  - GRIN lens to Capture wires
  - FPGA Bit Error Tester

- **850 nm LASER** for alignment
- **1550 LASER Beam**
- **Small Prism**
- **Asphere Lens** to launch Si Detectors
- **MEMS Mirror** to steer

- **Modulator**
- **FPGA**
- **Lookup table**, Digital filter

- **SFP**

- This Assembly moves

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Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.
Digital Processing MEMS Steering Setup

- **FPGA Pseudo Random Data, Bit Error Rate**
- **Modulator**
- **Launch Lens**
- **MEMS Mirror**
- **Quad Detector and Steering Laser**
- **Standard Fiber Receiver**

**RECEIVER**

- **Reflecting Lens**
- **GRIN LENS To Fiber**
Applications

LONG DISTANCES
ANL Long Range Free-Space Communication Telescope

1 Gb/s over 80 Meters

Only 0.5 mW because not $\frac{1}{r^2}$
Advances Made at Argonne

- Steering using reflections from the receiver system, without wires. We made a major improvement by separating data link and the alignment link.

- Found ways to form beams and receive beams that reduce critical alignments, reducing time and money for setup.

- 1.25 Gb/s over 1550 nm in air, using a modulator to impose data, and FPGA to check for errors, $<10^{-14}$ error rate, with target moving about 1 cm x 1 cm at 1 m.

- Control of MEMS mirror which has high Q resonance (using both Analog and Digital filter)

- Long range data Telescope using low power (0.5 mW vs 250 mW commercial) by means of near diffraction limited beams

- Some radiation testing of SiGe Modulator Material
Future Directions

- Develop at least a 5 Gb/s link in air (with digital feedback)
- More robust long distance optical link
- Evaluate
  - MEMS mirror supplied by Argonne CNM
  - Commercial modulators
- In addition, we have submitted a proposal to apply optical readout to an actual detector in the Fermilab test beam using Argonne DHCAL, which would be an ideal test-bed with 400K channels.
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**THE MIT DEVICE:**

**MEMS mirrors:**
Radiation hardness references

Radiation hardness of LiNO3:


