Free Space Optical Data Links

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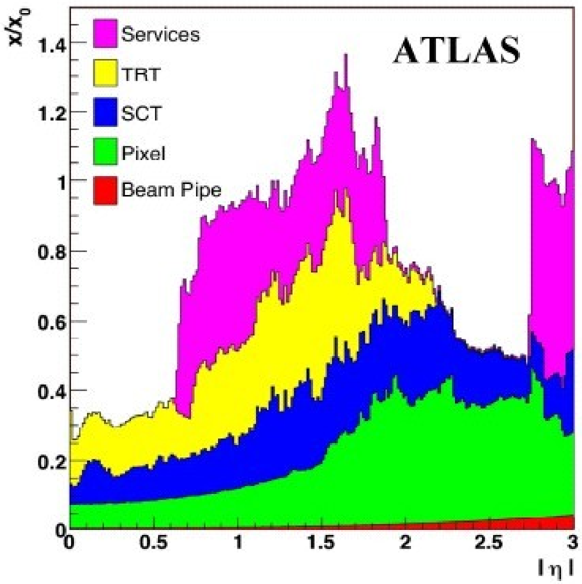
Our Original Motivation

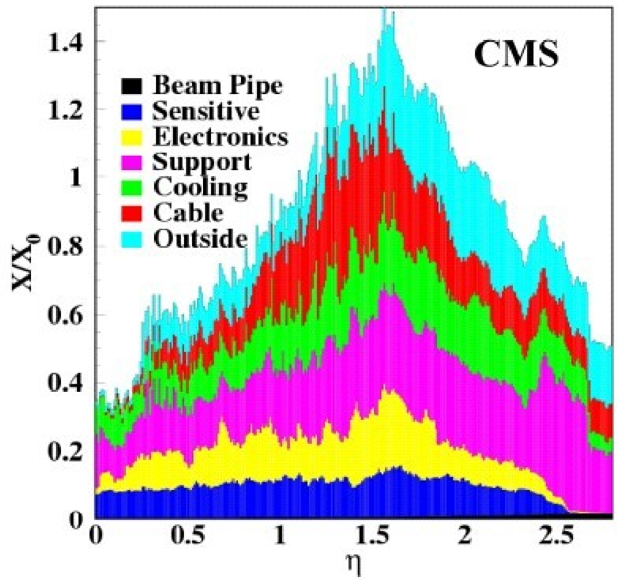
ATLAS/CMS: from design to reality

Amount of material in ATLAS and CMS inner trackers

Weight: 4.5 tons



Weight: 3.7 tons

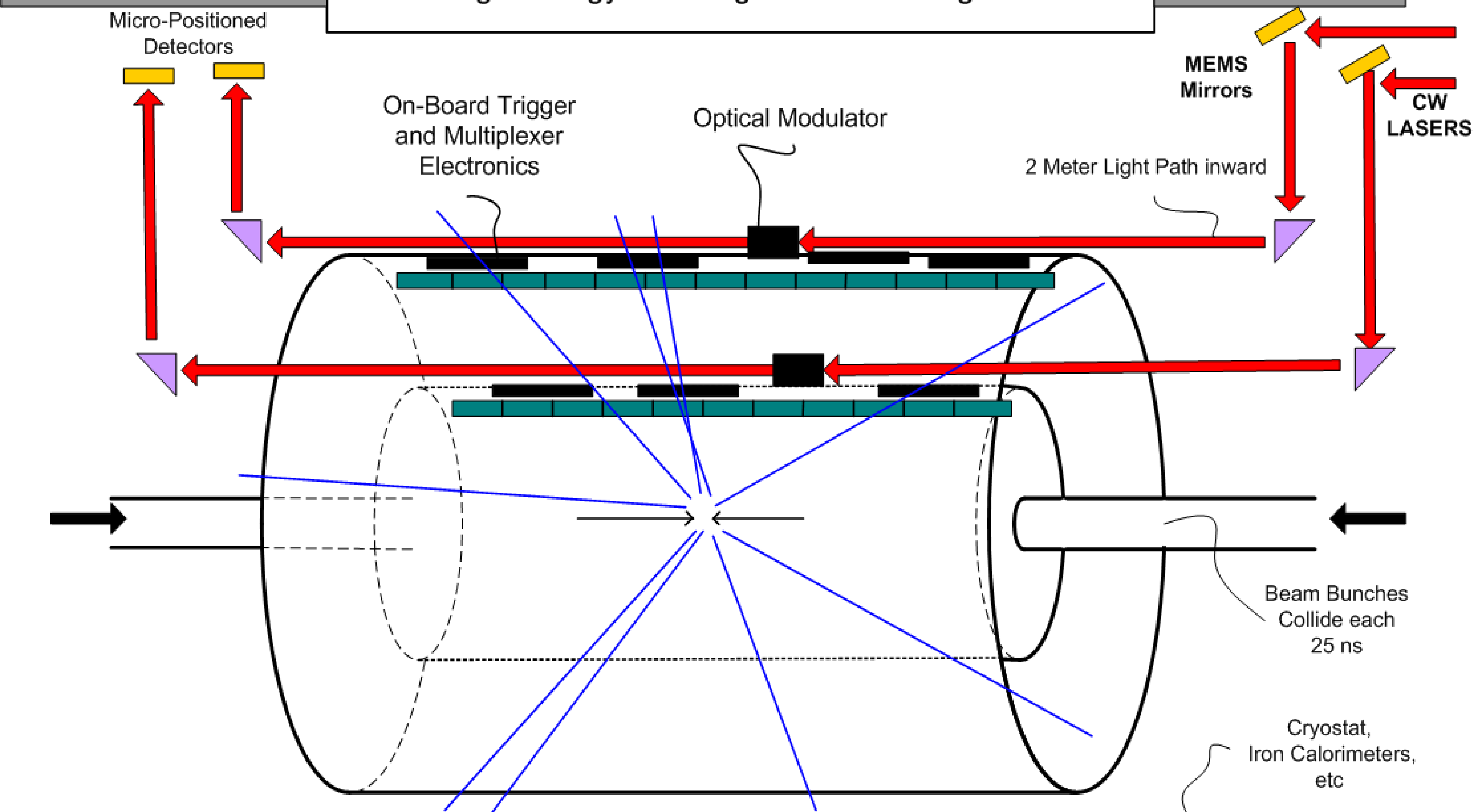


- Active sensors and mechanics ~ 10% of material budget
- 70 kW power into tracker and to remove similar amount of heat
  - Very distributed heat sources and power-hungry electronics inside volume
    - complex layout of services, most of which were not at all understood at the time of the TDRs

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

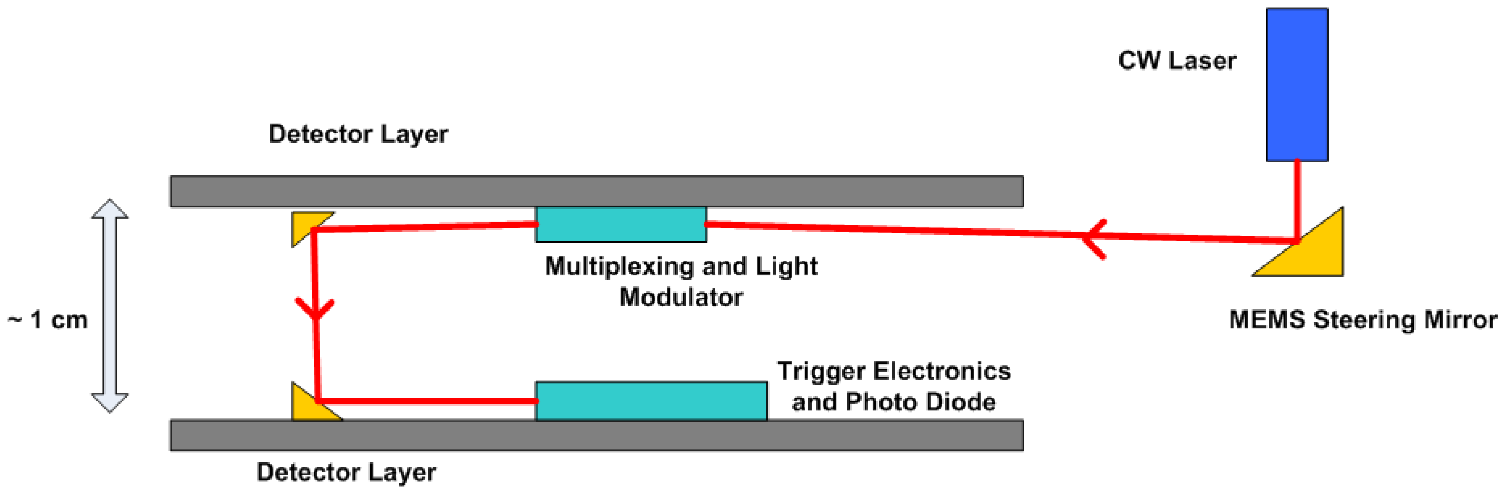


12 Tracking Cylinders, 10^7 Pixels, 1000 Optical paths

(down from 40000 fibers in existing CMS detector)

One concept

Concept of communication between ID layers for trigger decisions

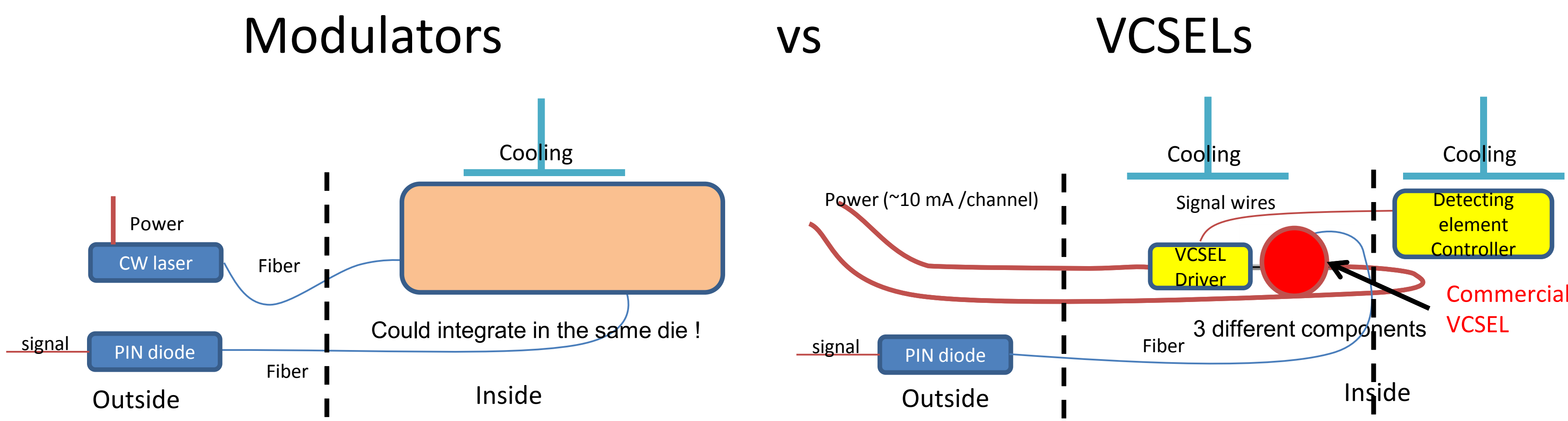


Some concepts for interlayer communication for input to trigger decisions

- 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

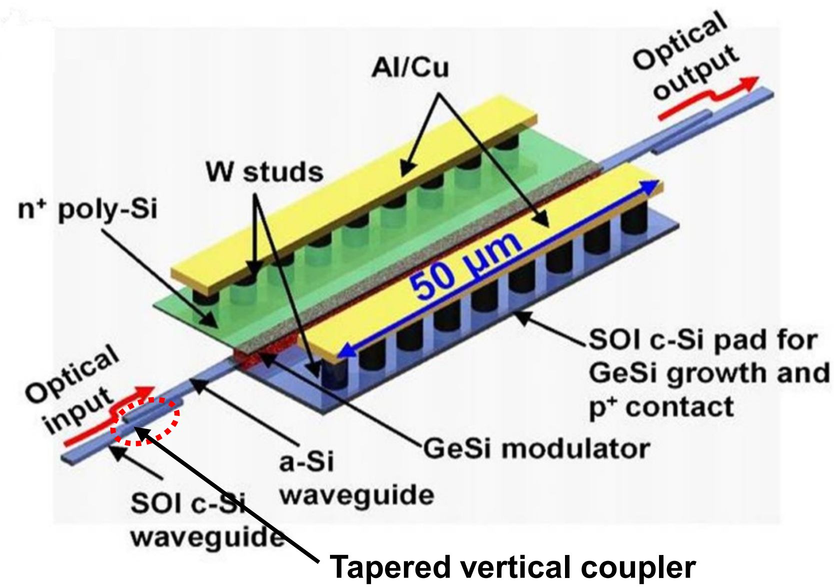
Technology : Modulators

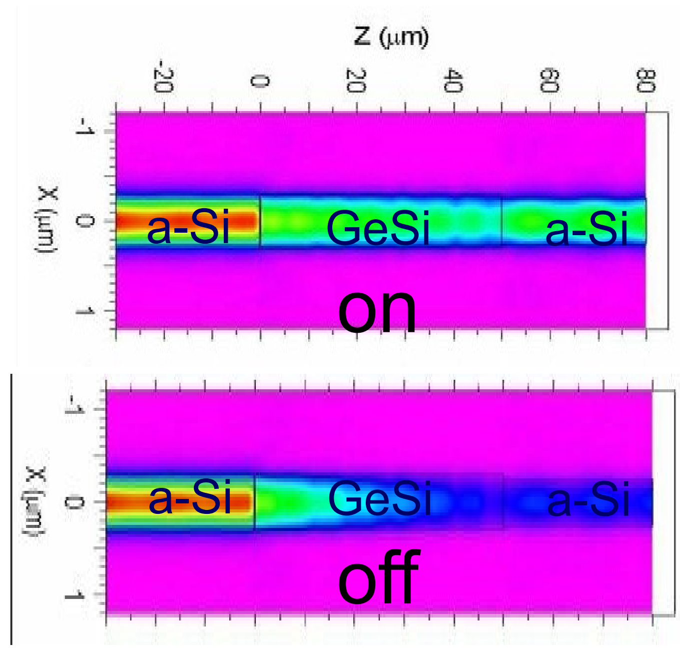


- Advantages:
  - High bandwidth: no chirp, no wires from detectors → commercial systems work >10 Gb/s/channel
  - Low material budget : Less Power inside detector → fewer wires needed→ less cooling needed
  - Higher reliability: Laser sources outside the detector, modulators can be integrated into a 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



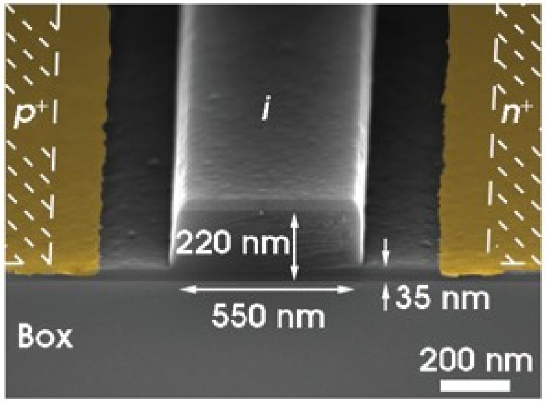


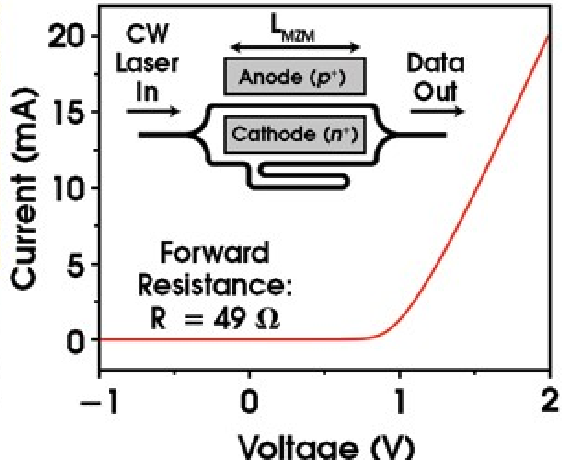
- Fabricated with 180 nm CMOS technology
- Small footprint (30 µm2)
- Extinction ratio: 11 dB @ 1536 nm; 8 dB at 1550 nm
- Operation spectrum range 1539-1553 nm (half of the C-band)
- Ultra-low energy consumption (50 fJ/bit, or 50 µW at 1Gb/s)
- GHz bandwidth
- 3V p-p AC, 6 V bias
- Same process used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

Liu et al, Opt. Express. 15, 623-628 (2007)

the MicrophotonicsCenter @MIT

Technology : Mach-Zehnder Modulators





41 mW at 5 Gb/sec

100 u long x 10 u wide

Thin, order u

Broad spectrum 7.3 nm at 1550

80 u long delay line internal

1V p-p AC, 1.6V bias

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

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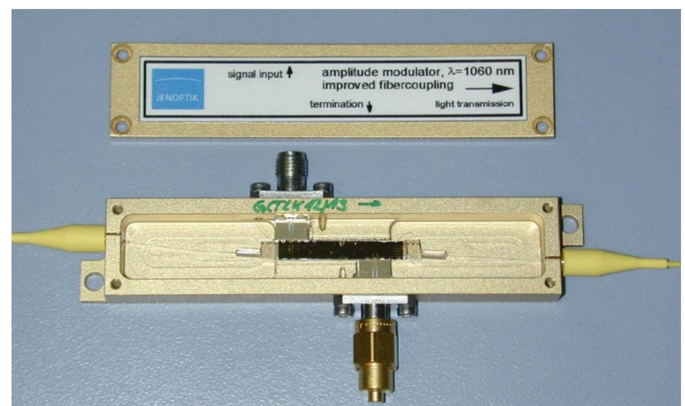
Abstract: Silicon p^{+}-i-n^{+} diode Mach-Zehnder electrooptic modulators having an ultra-compact length of 100 to 200 μm are presented. These devices exhibit high modulation efficiency, with a $V_{\pi}{\cdot}L$ figure of merit of 0.36 V-mm. Optical modulation at data rates up to 10 Gb/s is demonstrated 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 x $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



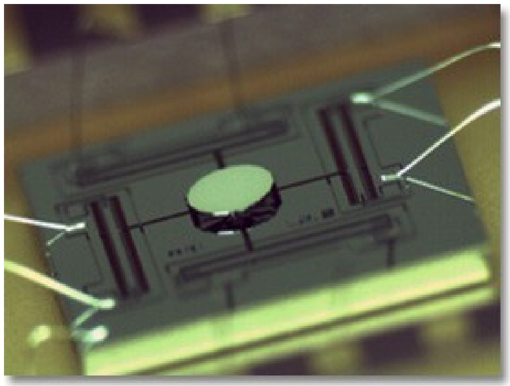
Active device
Approx. 1 Gram

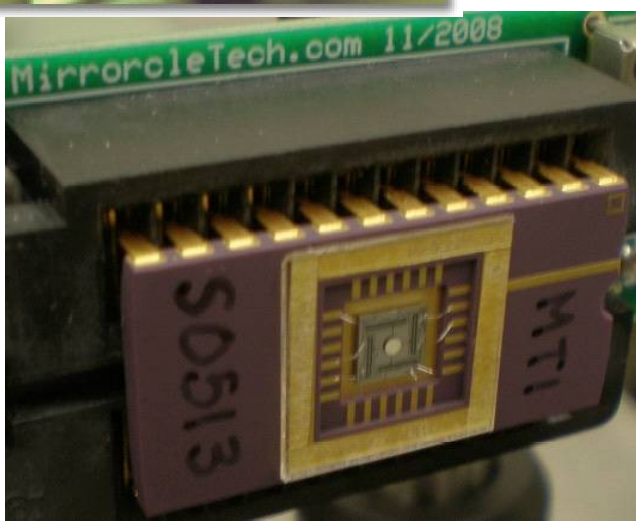
Technology : Free Space Data Links

- 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:

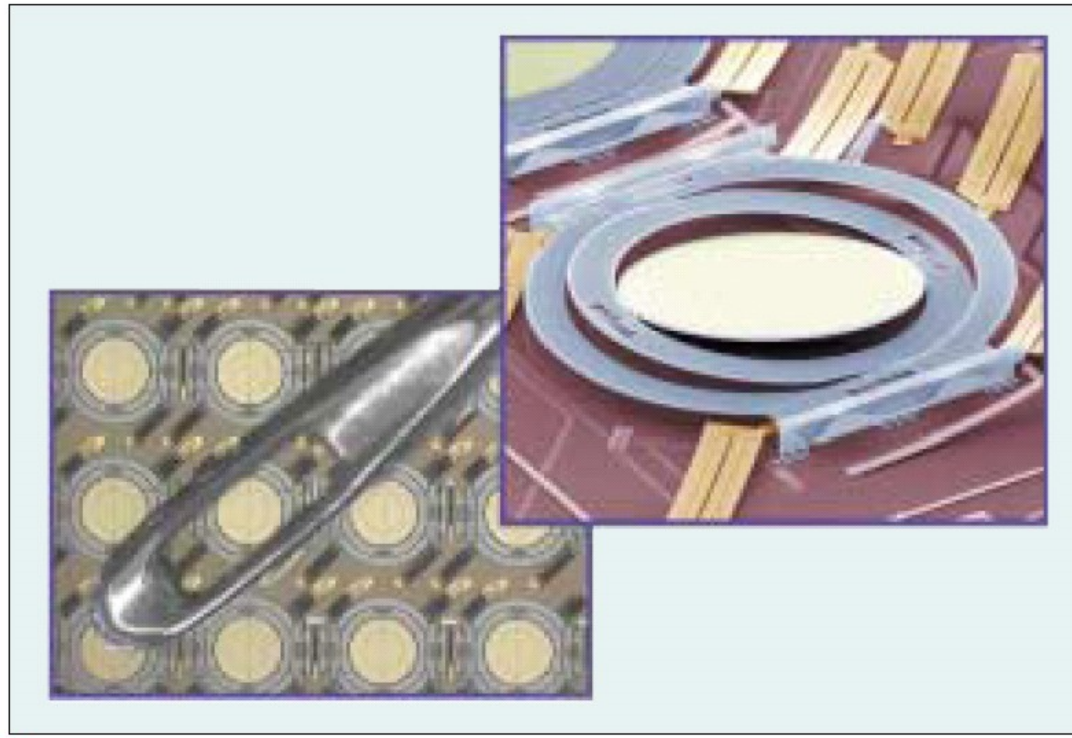
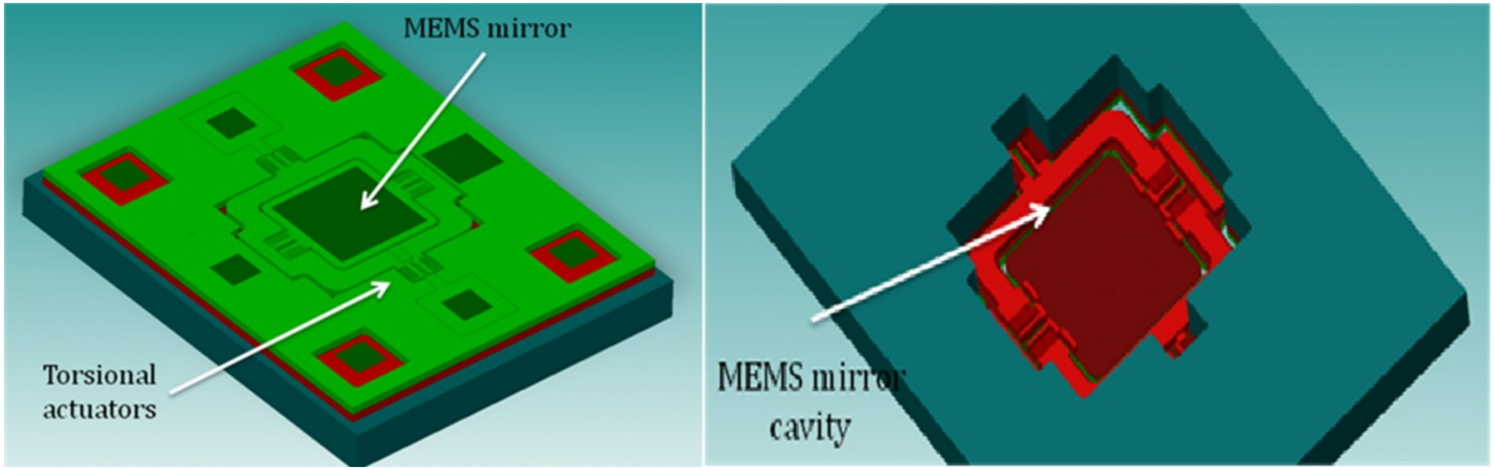


Figure 4. *Two images of MEMS-based OXC mirrors used in the Lucent LambdaRouter. The image in the upper right is a single mirror, and an array of mirrors is shown in the lower left. An eye of a needle is shown for comparison on the array.*

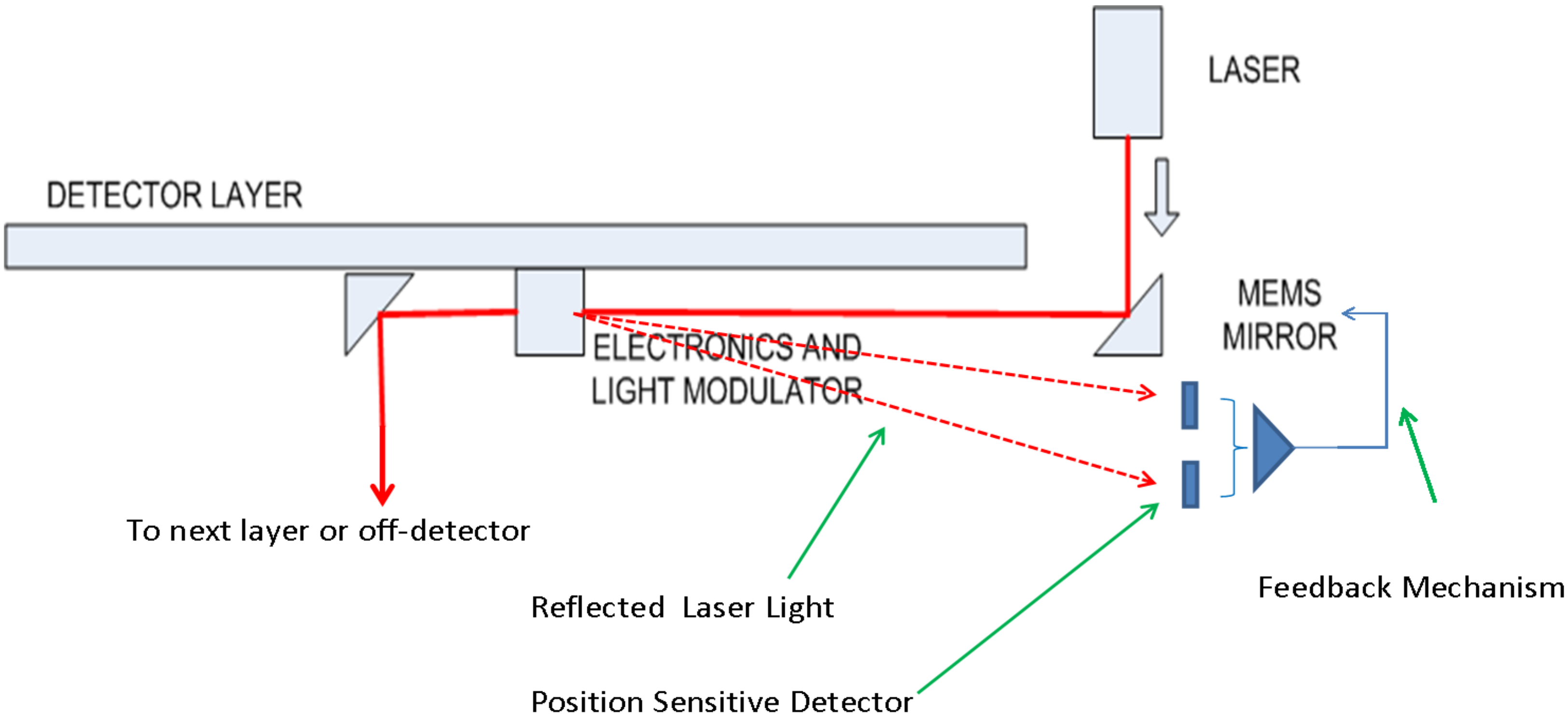
Technology : Argonne MEMS Mirrors

- 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.



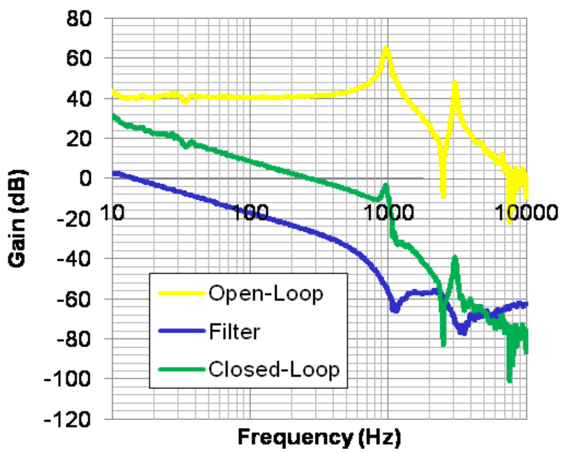
The figures show a 3D finite element analysis of the MEMS designed. The left panel shows the top view of the mirror and the right panel a bottom view.

ANL Concept of Direct Feedback to Establish and Maintain Stable Alignment

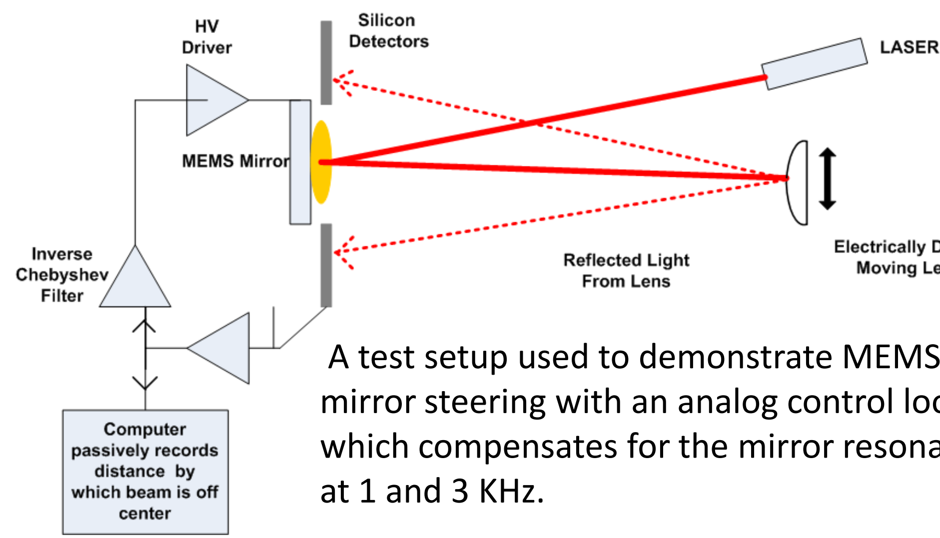


Studies of Direct Feedback Concept

- 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.

Beams in Air: Size vs Distance

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

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

Application

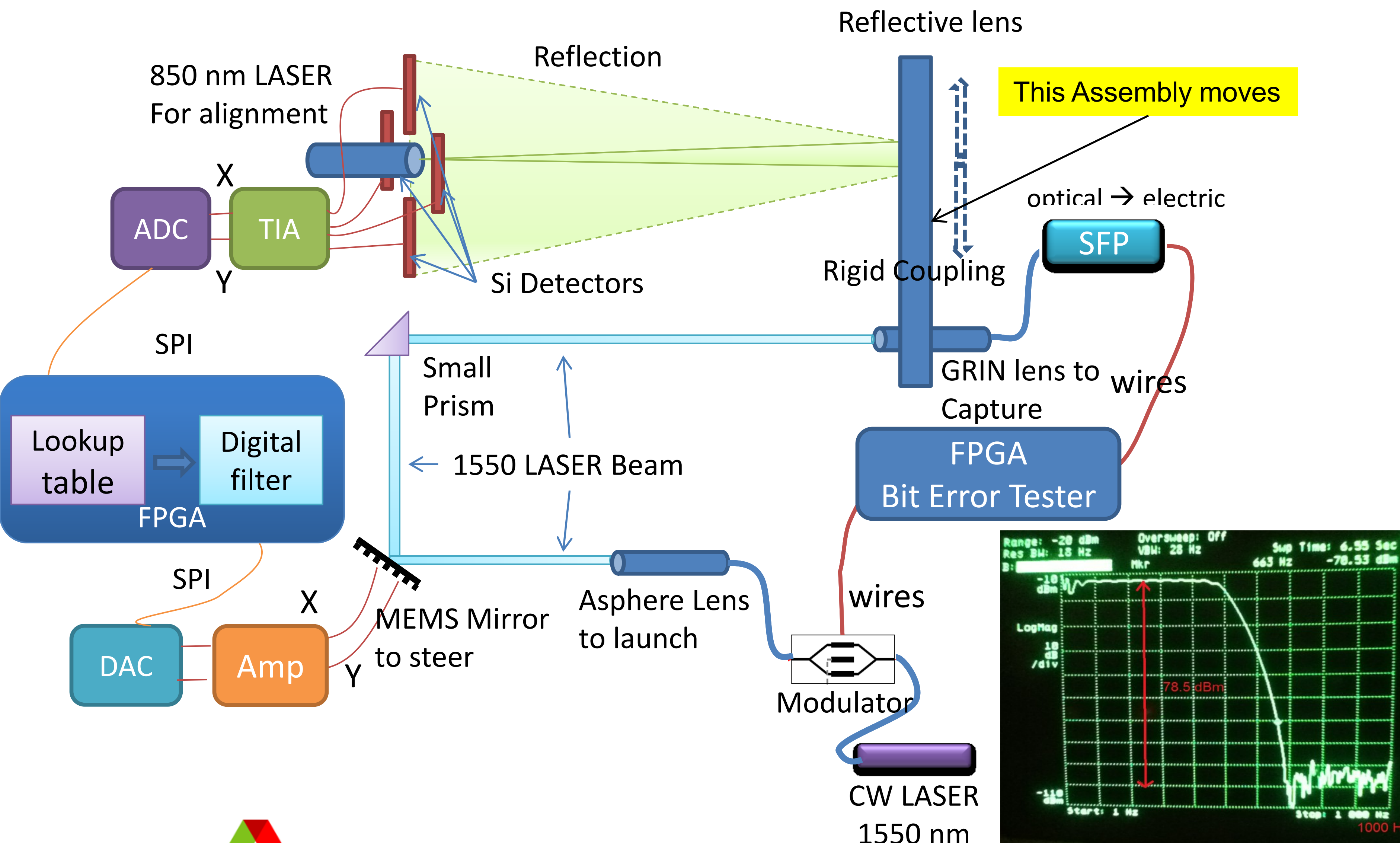
- Short/long distance
- Extreme low mass
- Very high speed
- Radiation hardness
- Reliability

APPLICATIONS

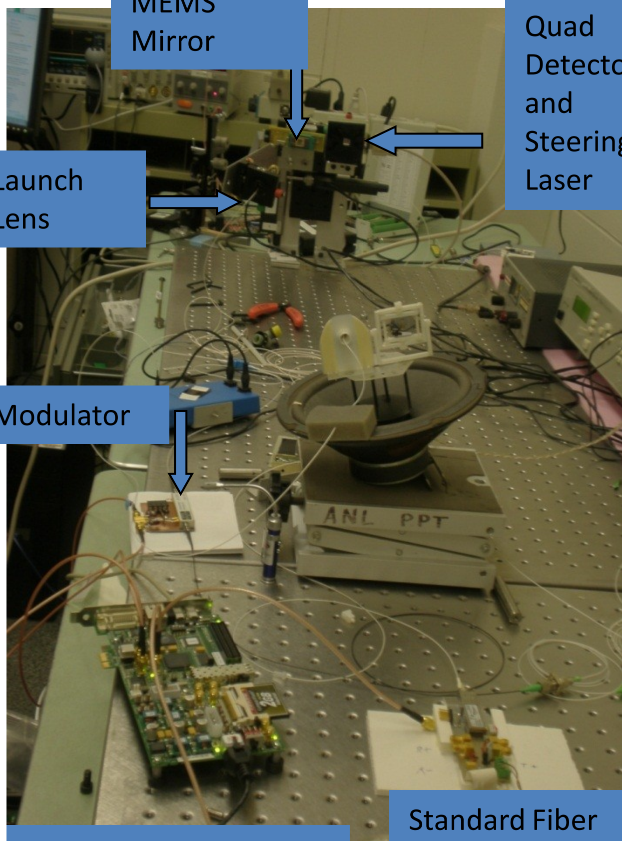
Applications

SHORT DISTANCES

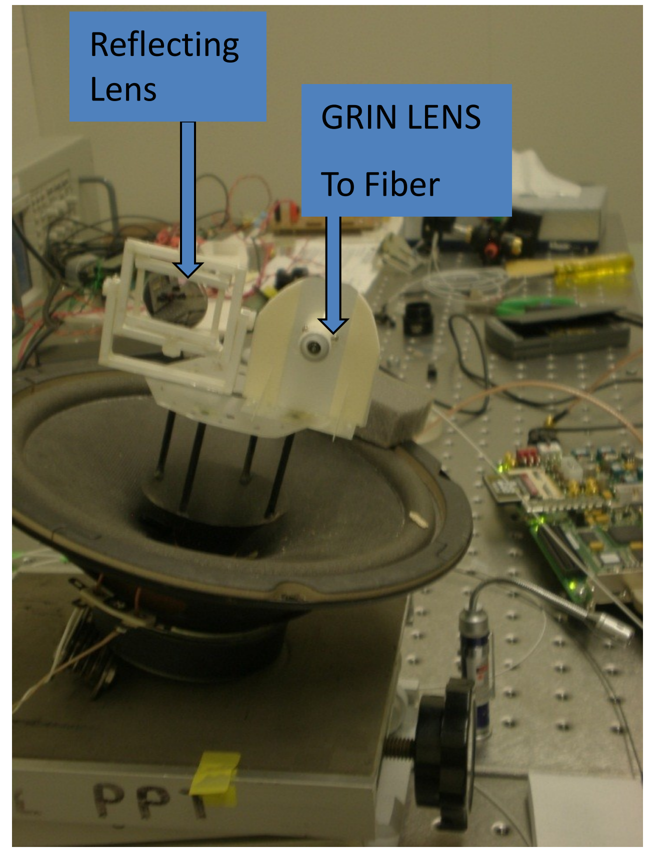
Our Current Version



Digital Processing MEMS Steering Setup



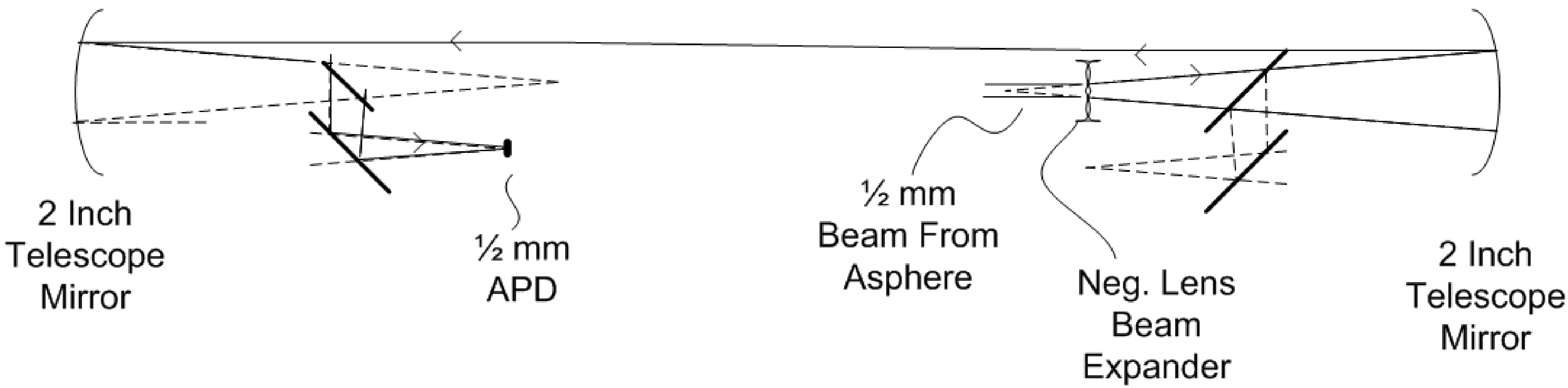
RECEIVER

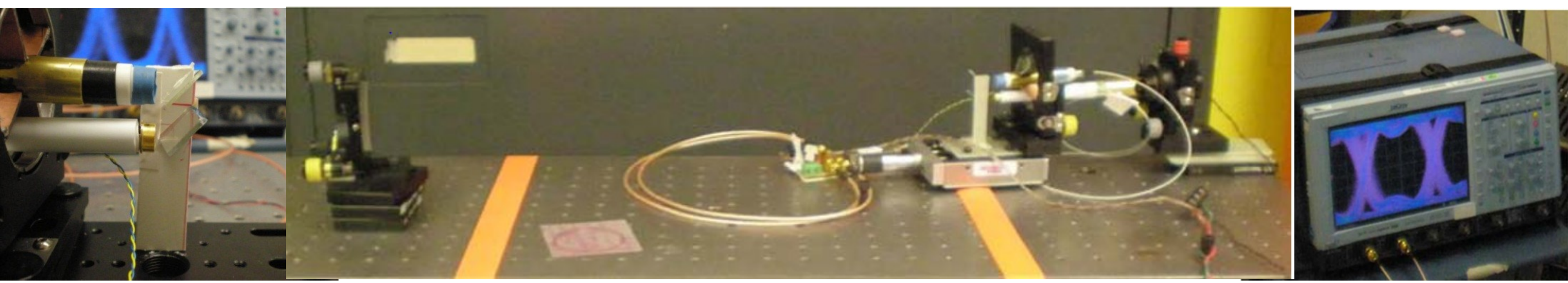


Applications

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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