New Optical Link Technologies for HEP Experiments

W.Fernando[1], P.M.DeLurgio[1], R. Stanek[1], B.Salvachua[1], D.Underwood[1] , D.Lopez[2]
[1] High Energy Physics
[2] Center for Nano-scale Materials
Argonne National Laboratory

Motivation

- Develop and adapt new technologies to improve optical communication in HEP experiments
  - Increase speed
  - Reduce the mass of the system
  - Increase reliability
- Test operation of new devices with the environmental conditions of
  - Noise/Vibrations
  - Radiation
  - Temperature, humidity ..etc.
- Introduce the technologies to real HEP detectors

Issues with Current HEP Optical Links

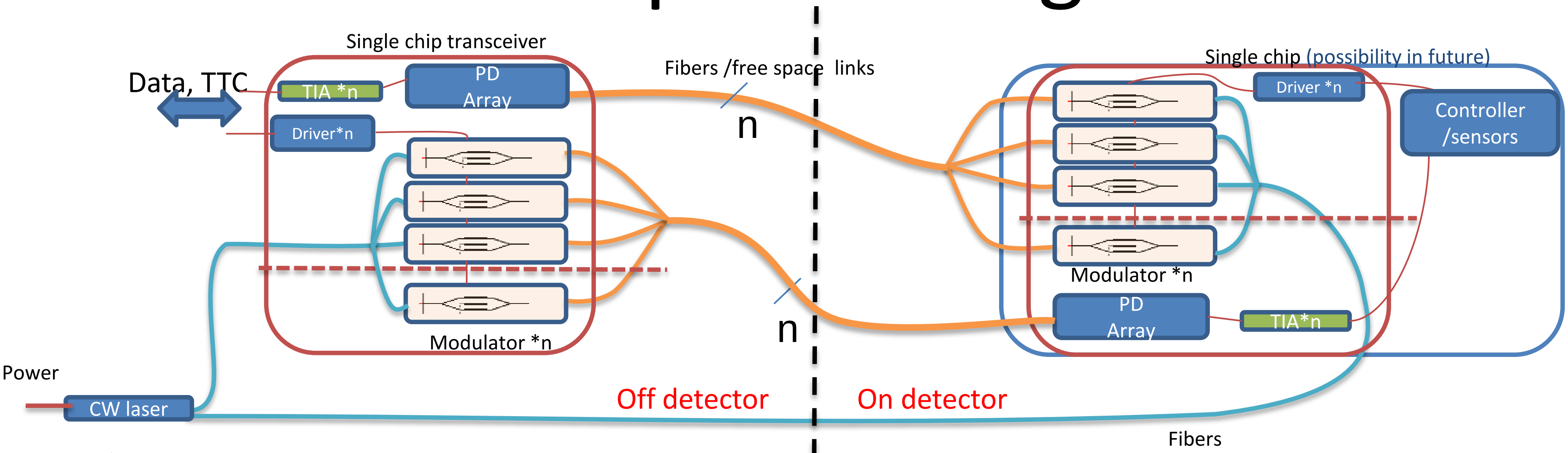
- Many HEP optical links use VCSELs* as laser source (on/off detector)
  - VCSELs
    - Need current driver chips: (radiation hard)
    - Need control wires to tune links
    - Power cables (to supply current)
    - Cooling/Heating
    - ESD/Humidity sensitivity
  - Components/Connectors
    - Many soldering joints or connectors
- Many optical link failures at LHC are due to VCSEL failures (DPF talk 392) & connectivity issues

Increase amount of material inside detector

Reliability issues

* VCSEL: Vertical Cavity Surface Emitting Laser

Conceptual Design

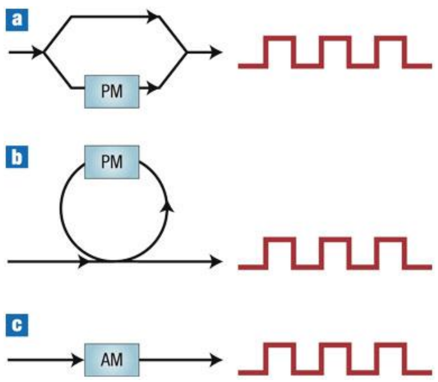


PD: photo diode
TIA: Trans Impedance Amplifier

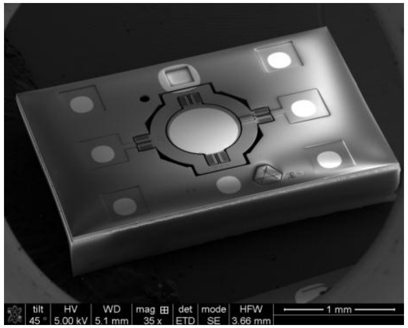
- **High bandwidth**:
  - Commercial systems work 40 Gb/s/channel
- **Low material budget** :
  - Less total power inside detector → less cooling needed
  - Fewer control wires needed
- **Higher reliability**:
  - Laser sources outside the detector
- **Integrated**
  - Modulators/PD (may be with module/sensor controller) can be integrated into a single die
  - Fewer connections

Key Technologies

- Modulators:
  - Different types made with
    a) Mach-Zender Interferometer (MZI)
    b) Micro Ring Resonator
    c) Electro Absorption (EAM)



- MEMS mirrors
  - Commercial /Argonne MEMS Mirrors



Argonne

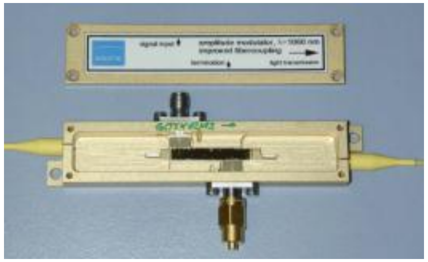
Argonne Center for Nan-scale Materials (CNM) developed novel MEMS mirrors that should solve the problems of commercial mirrors. The mirror is supported laterally and it can be actuated using 4 torsional actuators.

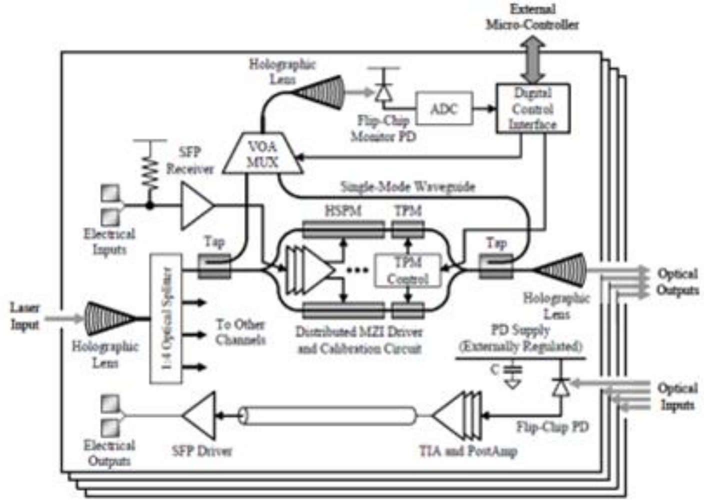
Key Technologies: Modulators

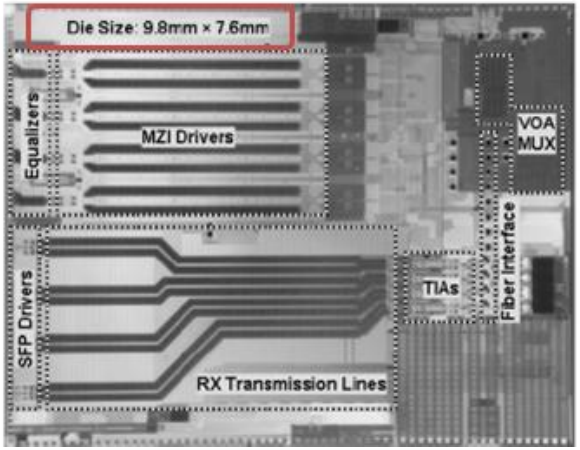
- Commercially available
  - LiNbO3 crystal based MZI : Radiation hard [1,2]

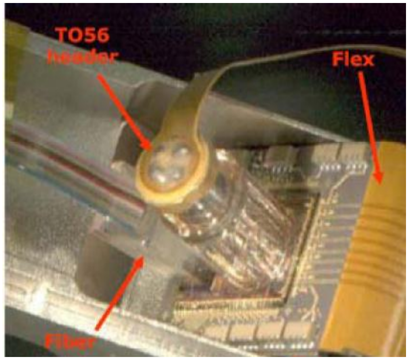
JENOPTIK will work with us [1]

  - Luxtera/Molex 0.13 µm CMOS SOI integrated 40 Gb/s single chip MZI modulator based transceiver. Molex will work with us to test the device and improve it [1,2,3]







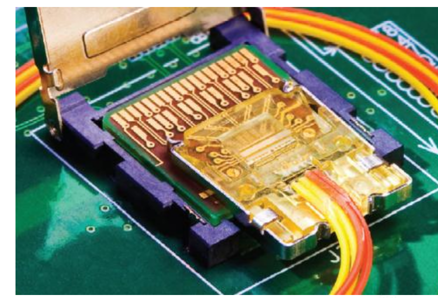


Key Technologies: Modulators (cont.)

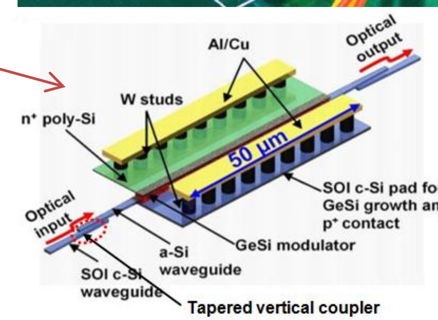
- Available Modulators
  - InP based 40Gb/s MZI modulators from Heinrich-Hertz-Institut Photonic Components.[1]

  - GaAs based 2x20Gb/s MZI modulators from u²t Photonics [1]

- R&D stage (not available for testing)
  - Si based 40Gb/s MZI modulators and 50Gb/s transceivers (WDM) from Intel [1,2,3]



  - GeSi EAM Device designed by MIT [1,2] GeSi radiation hardness [1]



  - Low power Si based 10Gb/s MZI modulator designed by IBM [1]

Testing Plan for Commercial Modulators

- Test Molex, Jenoptik, HHI (if possible u²t)
- Few Total Ionizing Dose (TID) testing rounds at ANL with electrons in next few months
  - Test unmodified devices first.
  - Feedback to manufacturer and request for modifications
- Testing for Lattice displacement and Single Event Effects (SEE) using 200 MeV Protons up to 10^{15} P/cm^2 by the end of 2011
  - Couple of batches (improve/unmodified..etc)

Technology : Free-Space Communication to Replace Fibers

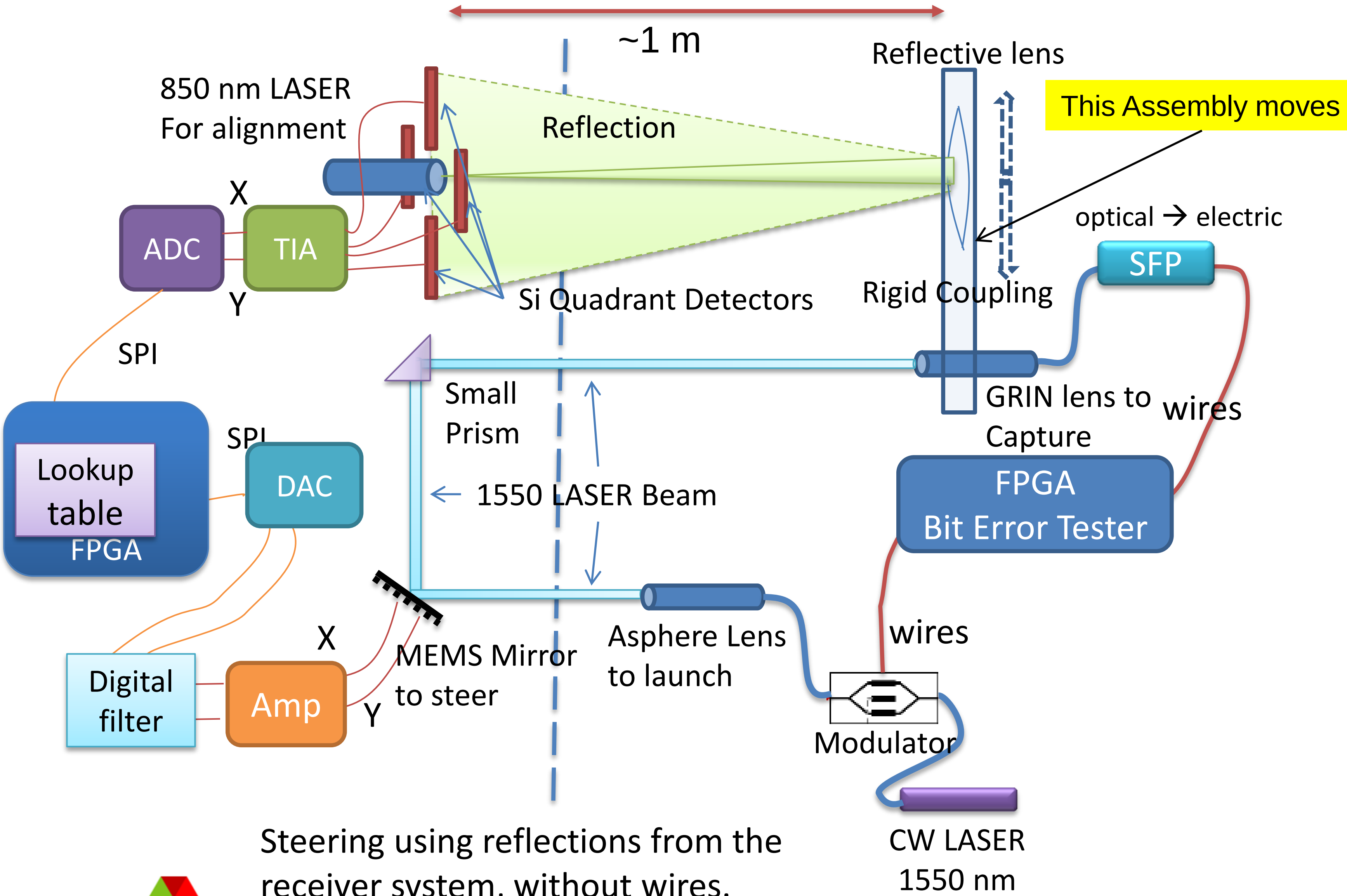
- Advantages:
  - Low mass
  - No fiber routing
  - Low latency (no velocity factor)
  - Low delay drift (no thermal effects such as in fibers)
  - Work over distances from few mm (internal triggers) to ~Km (counting house) or far (to satellite orbit)
  - Communicate between ID layers for trigger decisions.

Main Parts of Free Space Project

1. **Design of lens systems** to send and receive modulated laser light through free space
2. **Incorporate modulators** to modulate the laser beam
3. Use **MEMS mirror** to guide the beam to the receiver and the use of a **feedback mechanism** to keep the beam locked to the receiver
4. Setup for bit error rate testing
5. Demonstrate practical application, e.g. ANL DHCAL at Fermilab (this application not yet funded)

~ Completed

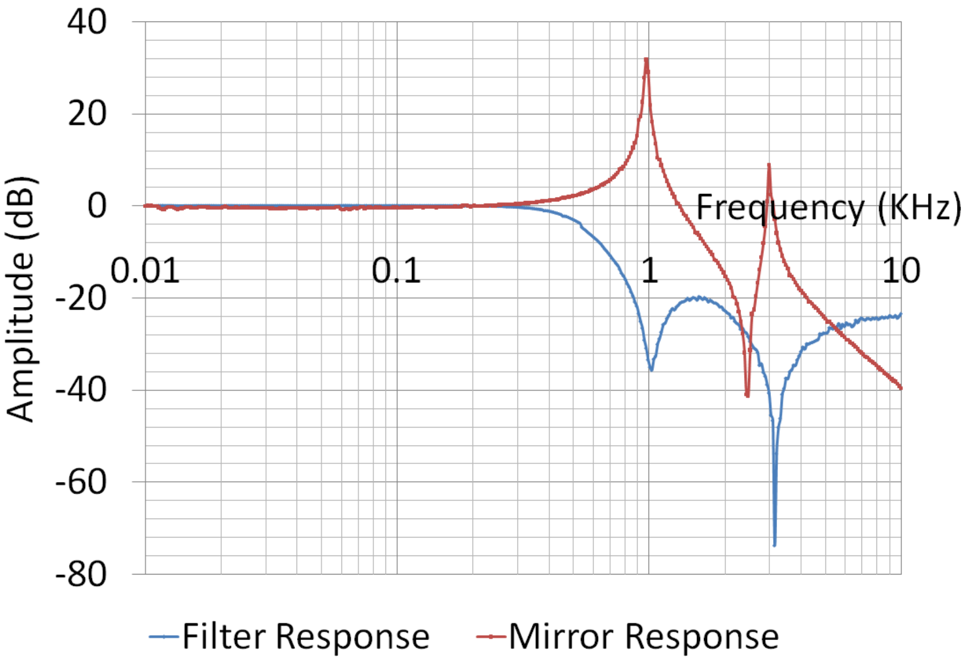
Our Current Version



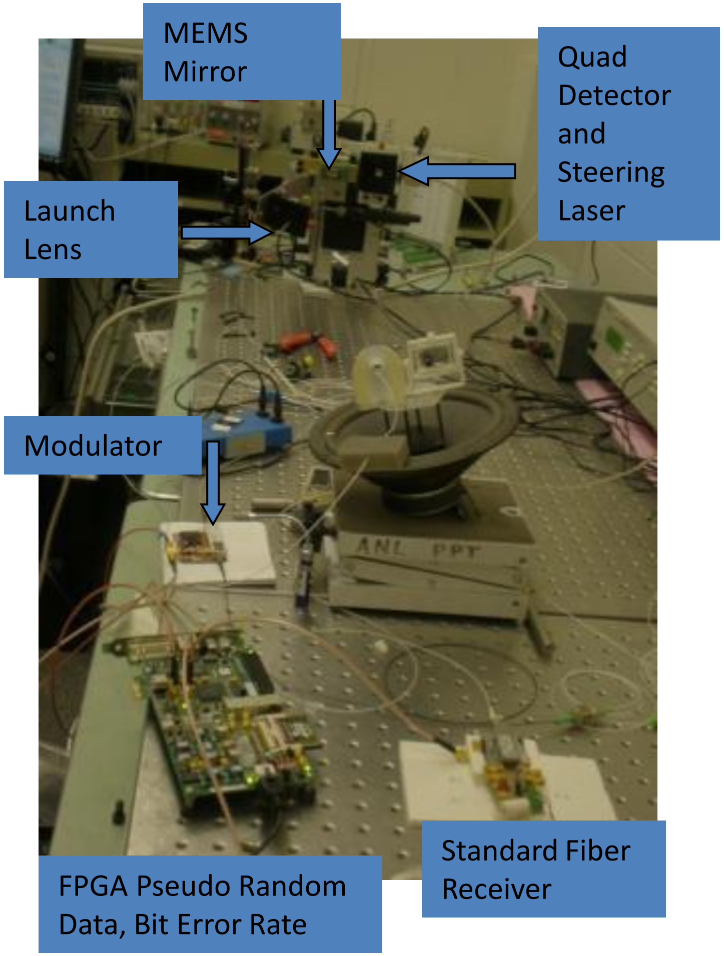
Steering using reflections from the receiver system, without wires.

Controlling Commercial MEMS Mirrors

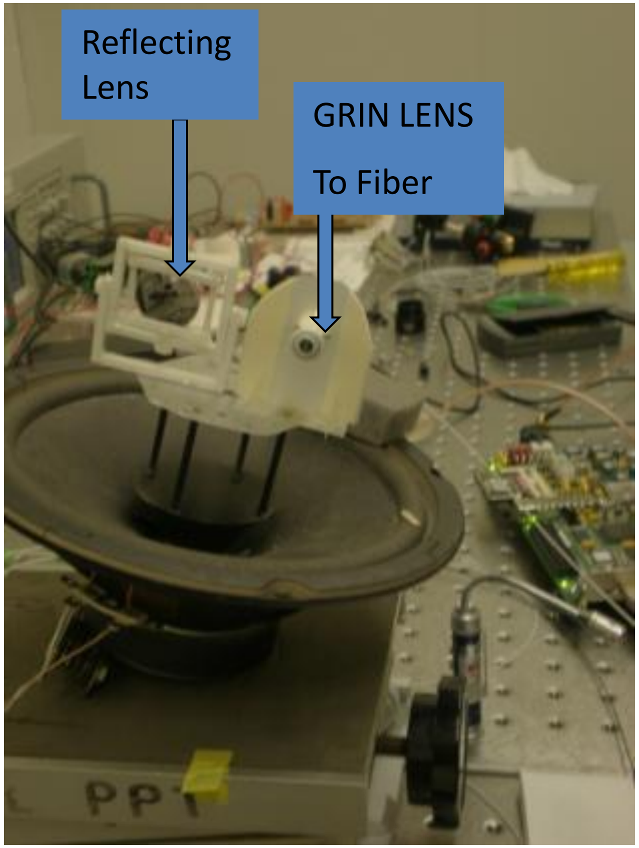
- A quadrant detector is used to read the reflection pattern
- Digitized quadrant detector input is used to map the location of the receiver (algorithm implemented in a FPGA)
- Digital output from FPGA is converted to analog signal
- Commercial MEMS mirrors have ~30 dB resonance peak at 1 and another one at 3 KHz
- Developed an inverse Chebyshev filter which has notches at 1 and 3 kHz, and appropriate phase characteristics



Digital Processing MEMS Steering Setup



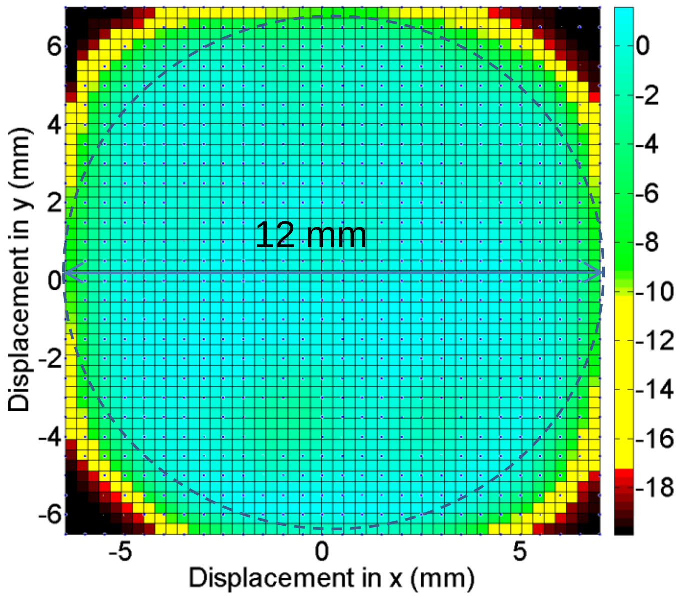
RECEIVER



Performance

- Static

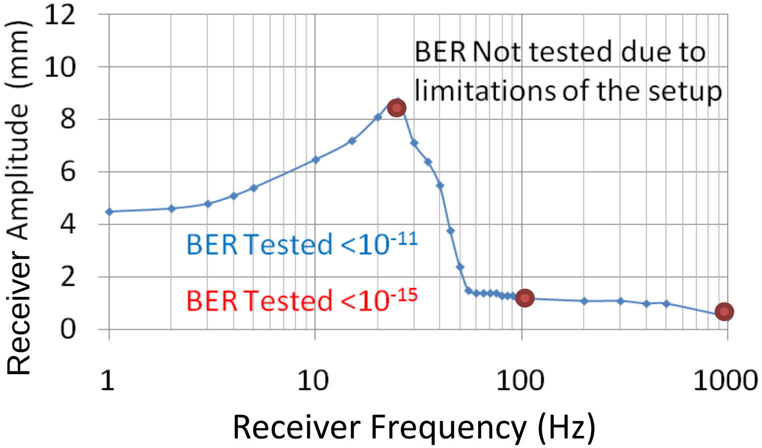
Received Optical Power (dBm)



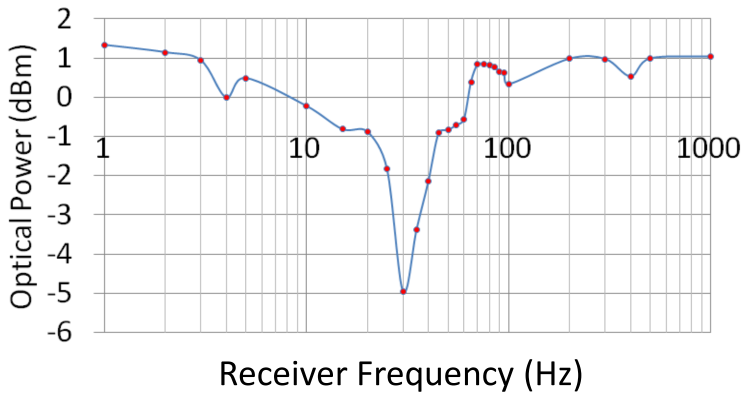
- Tested working range is adequate for detector environment

- Dynamic

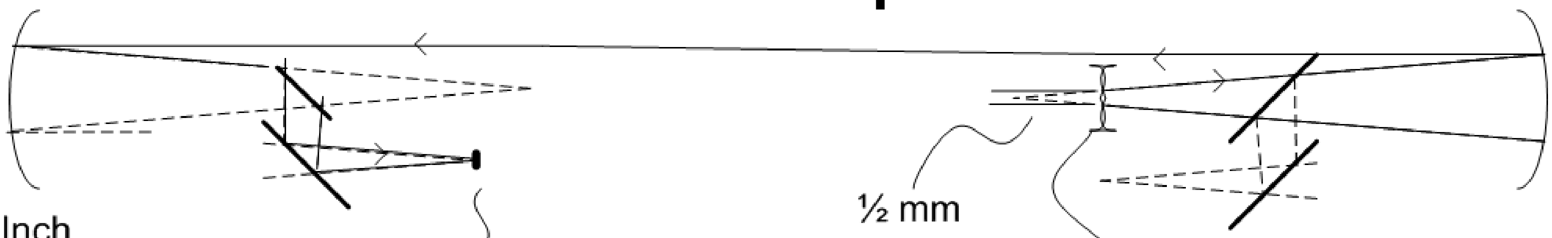
Tested Working Range of Moving Reciever

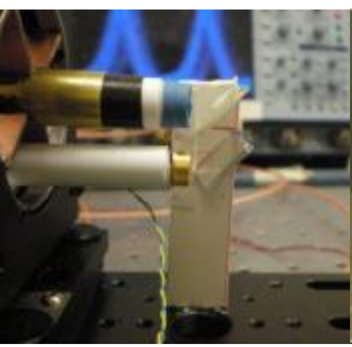


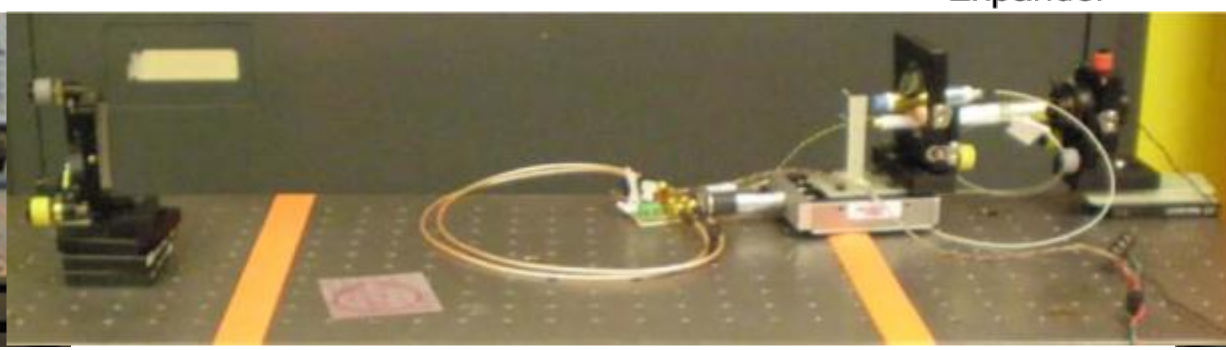
Received Optical Power at Highest Amplitude

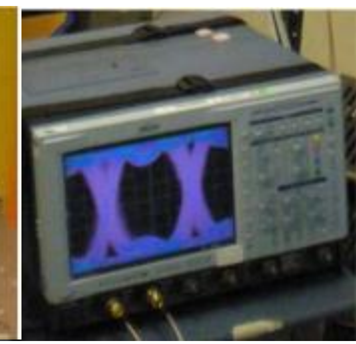


Long Range Free-Space Communication Telescope









Only 0.5 mW because not $\frac{1}{r^2}$

1.25 Gb/s over 80 Meters

Building a fast small distance positioner for the receiver with tiny servos

Accomplishments in Beams in Air

- 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.
- Control of MEMS mirror which has high Q resonance (using both Analog and Digital filter)
- 1.25 Gb/s over 1550 nm in air, using a modulator to impose data, and FPGA to check for errors, $<10^{-15}$ error rate, with target moving
- 1.25 Gb/s link using 850 nm in air for 80 m

Future Directions

- Short term
  - Test radiation hardness and quality of commercial modulators and improve those for HEP optical links
  - Build a modulator based optical link for future HEP detector and integrate to a real detector
- Long term
  - Build radiation hard modulators if funding obtained (collaboration with industry and Fermi Lab)
  - Develop 5 Gb/s link in air
  - Incorporate ≥2 MEMS mirrors
  - More robust long distance optical link
  - Local triggering using optical communication between tracking layers

Fiber based

Fibreless

Backup

Optical links failures at LHC

VCSEL failure Analysis (DPF 2011)
 http://indico.cern.ch/contributionDisplay.py?sessionId=10&contribId=392&confId=129980

VCSEL failures in ATLAS before beam
 http://www.sciencedirect.com/science/article/pii/S0168900208010474

VCSEL failures meeting
 https://indico.cern.ch/getFile.py/access?contribId=8&resId=0&materialId=slides&confId=103879

ACES meeting on optical links
 https://www.ncc.unesp.br/its/attachments/download/119/OptoWG_ACES2011.pdf shows few failures in CMS

TWEPP 2010 CMS operations "We continue to have failures of the optical links" (off detector)

https://wiki.lepp.cornell.edu/lepp/pub/People/AndersRyd/100924_TWEPP.pdf

LHCB VCSEL failures
 https://indico.cern.ch/getFile.py/access?contribId=3&sessionId=0&resId=1&materialId=slides&confId=126772

CERN Twiki on VCSEL failures (TT and IT) https://lbtwiki.cern.ch/bin/view/ST/VCSELs

Key Technologies: Modulators (summary)

Manufacturer/ Design	Type	Speed (Gb/s)	footprint	Modulation Voltage	Modulation Depth	Insertion loss
Jenoptik	MZI ($LiNbO_3$)	5	~ cm^2	5 V	20 dB	5 dB
Molex (transceiver)	MZI (SOI)	4x10	~cm^2 (transceiver)	Int. driver	20 dB	2 dB
HHI	MZI (InP)	40	packaged	2.8 V	> 20 dB	8 dB
u^2t	MZI(GaAs)	40	packaged	-	-	-
Intel	MZI	40	10^4 μm^2	6.5 V	20 dB	7 dB
MIT	EAM (GeSi)	1.2	10^2 μm^2	3 V	8 dB	5 dB
IBM	MZI (SOI)	10	10^3 μm^2	1.6V	-	-

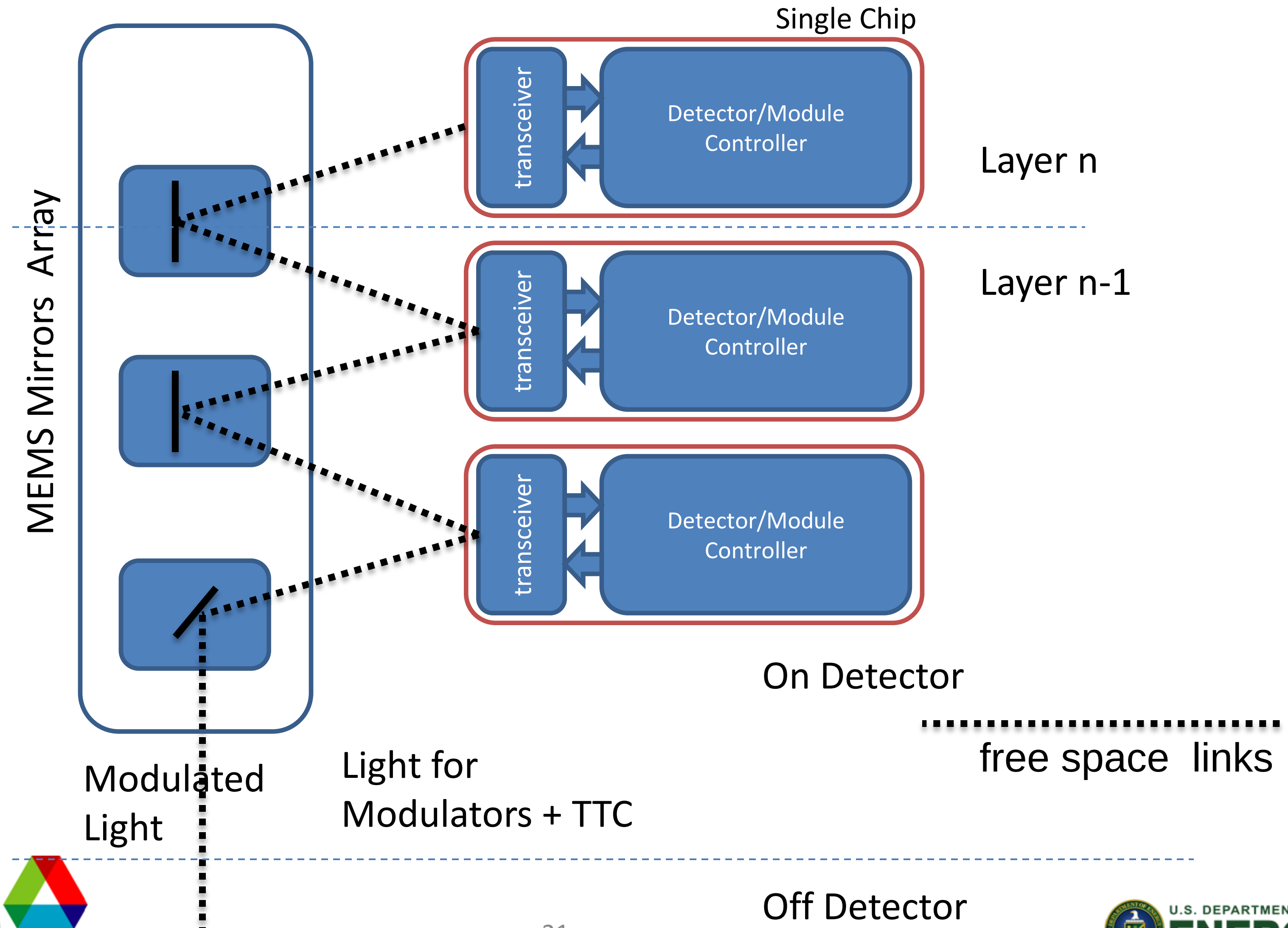
Argonne NATIONAL LABORATORY

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

U.S. DEPARTMENT OF ENERGY

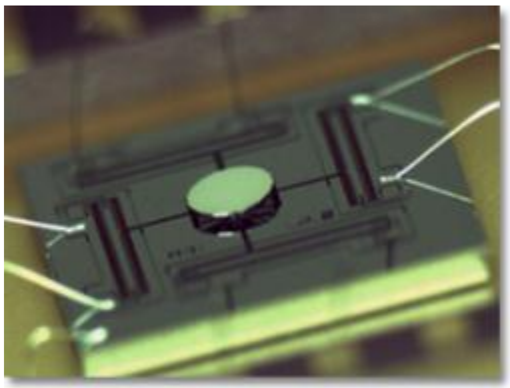
Conceptual Design (Advanced Stage)

Possibility for interlayer communication for triggering



Technology : MEMS Mirrors

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



The Lucent Lambda Router:

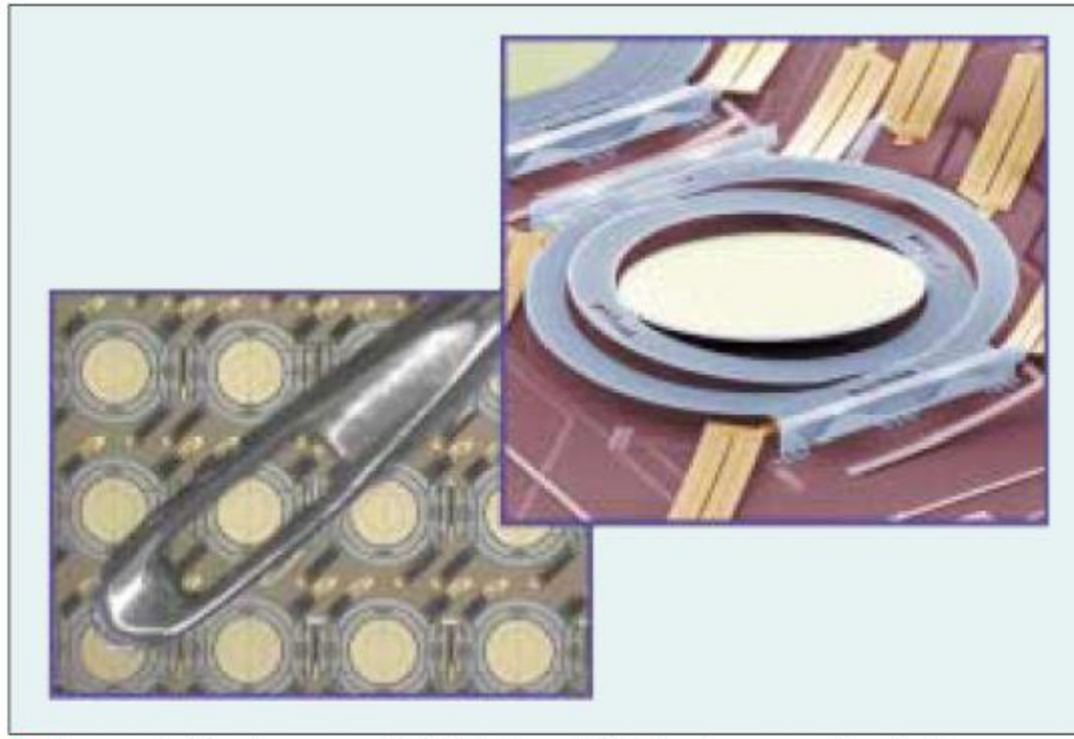
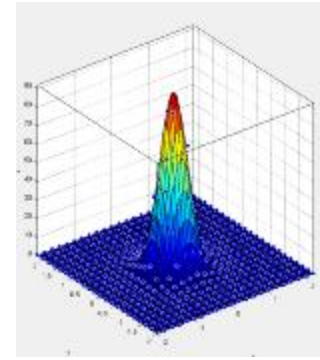


Figure 4. *Two images of MEMS-based OXC mirrors used in the Lucent LambdaRouter. The image in the upper right is a single mirror, and an array of mirrors is shown in the lower left. An eye of a needle is shown for comparison on the array.*

The Lens System(s)



- Studied in detail the properties of asphere and GRIN lenses to find the best option to send/receive the laser beam in air
- Transmitter on MEMS mirror (Data Laser)

Asphere Lens Type	Beam FWHM (mm) at 1m	Beam Peak Power at 1m (uW/(0.2 x 0.2) mm^2)
Short (EFL=6.24mm)	1.00	96.51
Medium (EFL=11 mm)	1.68	39.22
Long (EFL=15.3 mm)	2.26	22.60

- We knew that aspheres can produce the best beam to transmit but aspheres have very restricted acceptance angle. Important for capture lens.

Lens Types	Beam FWHM (mrad) at 1m		Total Captured Peak Power (μW)
	θ	ϕ	
Short Asphere (EFL=6.24mm)	1.64	1.73	179.7
Long Asphere (EFL=15.3 mm)	2.09	1.82	198.4
GRIN with SM	2.66	2.81	48.9
GRIN with MM	20.34	18.60	85.11

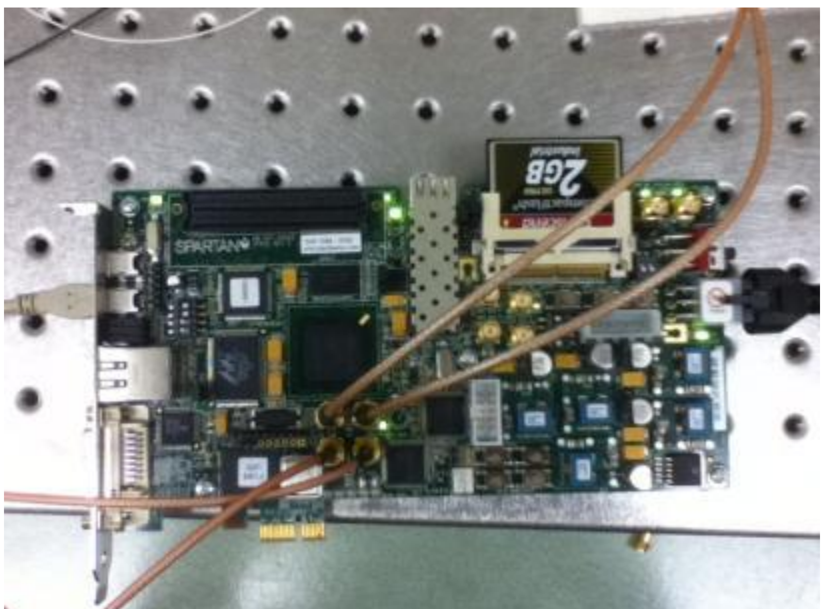
Beams in Air: Size vs Distance

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

Bit Error Tester

- FPGA based bit error tester that can be customized for
  - line rate, datapath width, TX pre-emphasis and post-emphasis, TX differential swing, RX equalization
  - Different patterns PRBS 7-bit, PRBS 15-bit, PRBS 23-bit, PRBS31-bit, user defined.



- Control through the computer to sweep , TX pre-emphasis and post-emphasis, TX differential swing, RX equalization, Rx sampling point to optimize the error free region

Plans for Beyond 2011 with FermiLab and Vega-Wave

- Testing improved modulators for reliability with MIL /Telcordia standard with additional radiation requirements
- Design and construct a radiation-hard silicon modulator chip if non of the commercial modulators satisfy radiation hardness
- Building a platform technology with modulators on silicon optical bench
- Communication within module/sensor control chips to improve the trigger efficiency (with or without wireless links)