New Optical Technology for Low Mass Intelligent Trigger and Readout

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We discuss a number of Optical technologies relevant to

low mass,   low power, high bandwidth

data paths between back-to-back tracking layers for the purpose of on-board triggering.

These same technologies can be used to reduce the mass, power, and fiber plant of readout from a tracker.

We are particularly interested in light modulators which can be integrated into CMOS chips, and MEMS mirrors for directing light beams.

Reasons for Optical Modulators:

Very little electric power : laser is outside tracking volume

Integrated into CMOS , e.g. GBT-like, multiplexers

Communicate between chips with no copper

(MIT, IBM, Intel, … are developing devices for beams between chips)

Reasons for Beams in air :

Size of connections between Detector layers

Small Lenses and Mirrors - No fiber connectors

Replace fibers

No fiber mass

No fiber plant / fiber routing

Possibly more rad. hard – needs more study

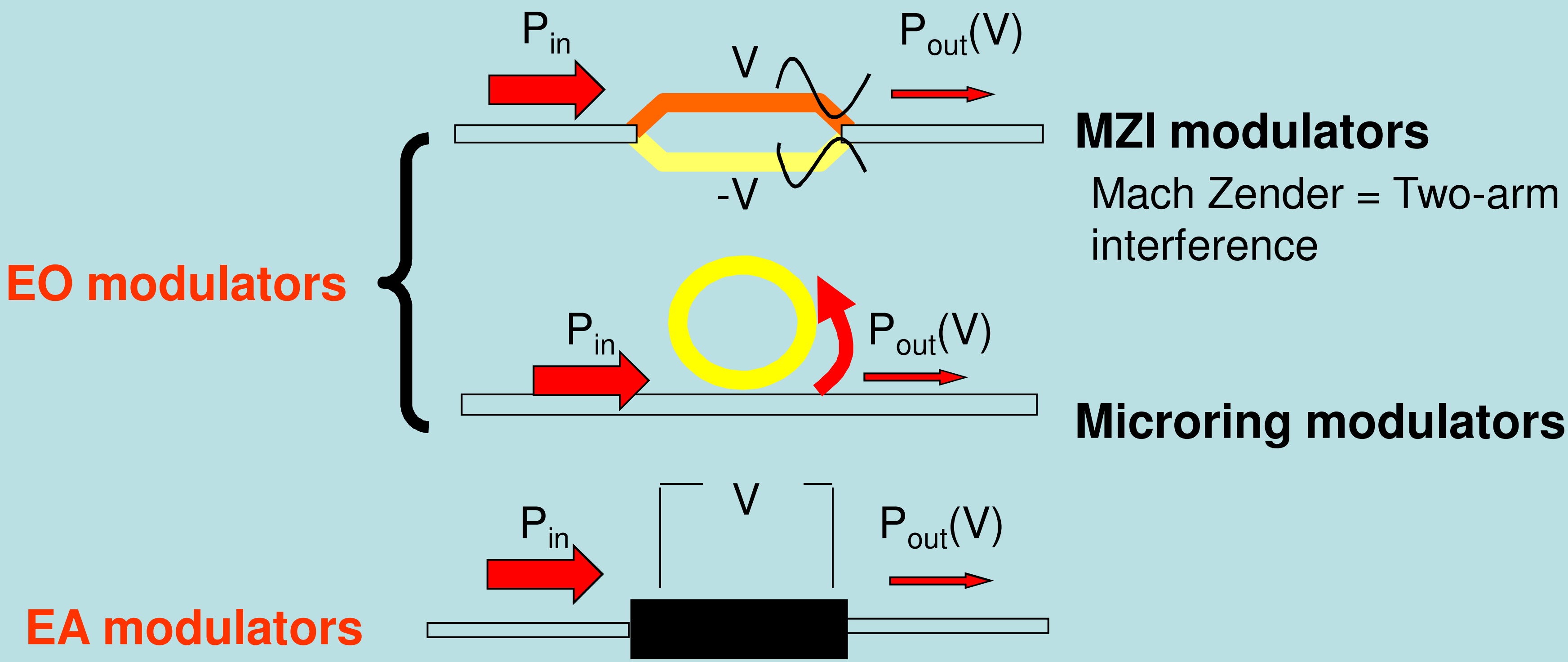
Claimed to be cheaper (Harvard Broadband Lab and LBL…)

Tracking Trigger utilizing combined Beams and Modulators

Low-mass, broadband link between tracking layers

Separate issue is getting data out using beams with MEMS mirrors

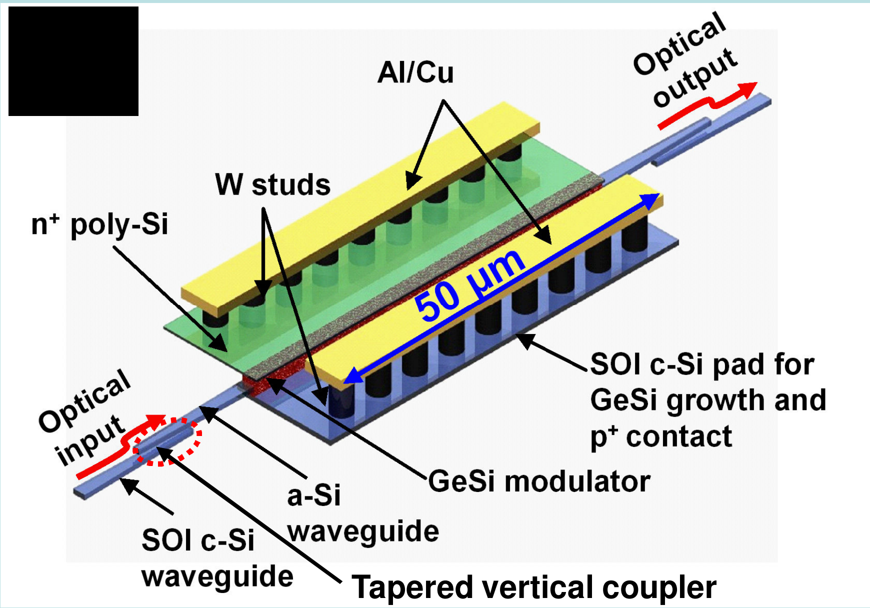
Electro-Optical vs. Electro-Absorption Modulators

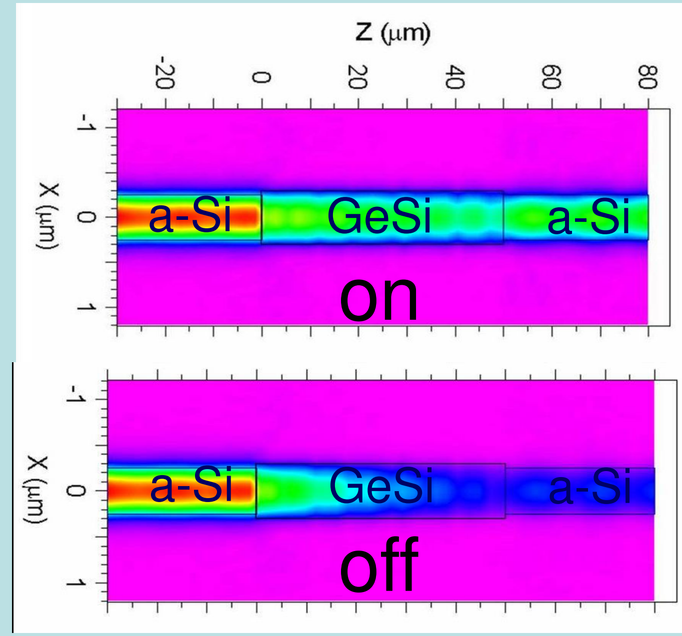


- EO modulators are based on the index change (Δn) .
  - MZIs typically large (mm in length) and power hungry
  - Mirocrorings very compact yet with limited operation spectrum range (~1 nm)
- EA modulators are based on field-induced absorption change ($\Delta\alpha$).
  - Compact (<100 µm), low power consumption, ultrafast intrinsic response (<1 ps)
  - ~20 nm operation spectrum width

EAM are Ideal for integration!

MIT Design of GeSi EAM Device Structure





- Butt-coupling scheme adopted for easier process integration
- 10 dB extinction ratio at 1550 nm with ~4 dB insertion loss is predicted
- The same material and device structure can be used for both EA modulator and photodetector

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

Ultralow Energy, Integrated GeSi Electro-Absorption Modulators on SOI

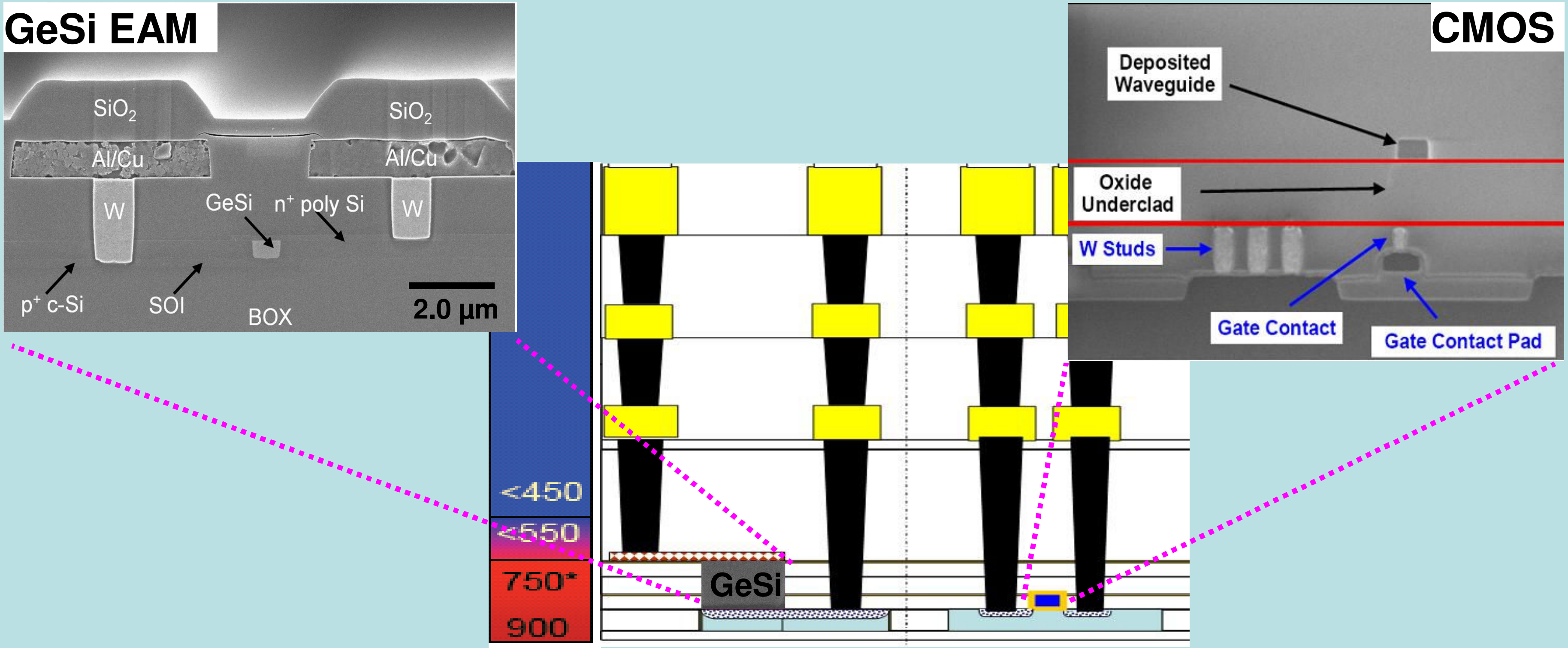
Jifeng Liu, Sarah Bernardis, Jing Cheng, Rong Sun, Mark Beals, Lionel C. Kimerling, and Jurgen Michel
Microphotonics Center, Massachusetts Institute of Technology

Andrew T. Pomerene
BAE Systems, Semiconductor Technology center

- **Fabricated with 180 nm CMOS technology**
- **Small footprint (30 μm^2)**
- **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**

Acknowledgement
- **EPIC Program, Defense Advanced Research Projects Agency (DARPA).**

Integration of GeSi EAMs into CMOS Process



- **GeSi grown between front and backend of CMOS process for electronic-photonic integration.**
- **Two-step UHVCVD GeSi selective growth:**

(1) a 30-60nm GeSi buffer at 360C; (2) rest of the growth at 600-700C
Annealing at 800-850C decreases dislocation density to ~$10^7/cm^2$
CMP to remove top facets

M. Beals et al, Proc. SPIE. 6898, 689804 (2008)

IBM

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.

41 mW at 5 Gb/sec

100 u long x 10 u wide

Thin, order u

Broad spectrum 7.3 nm at 1550

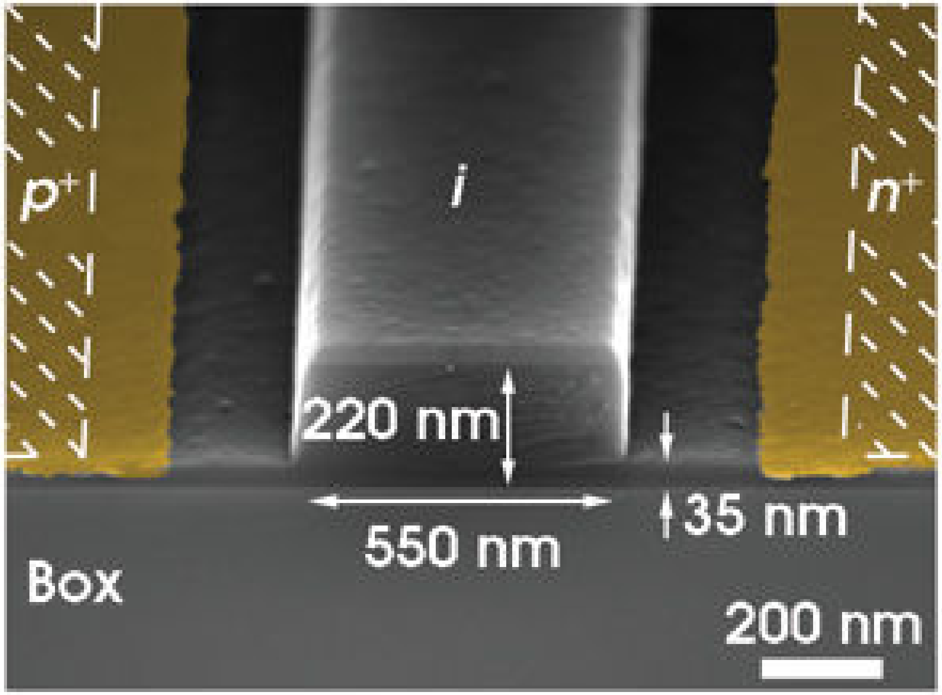
80 u long delay line internal

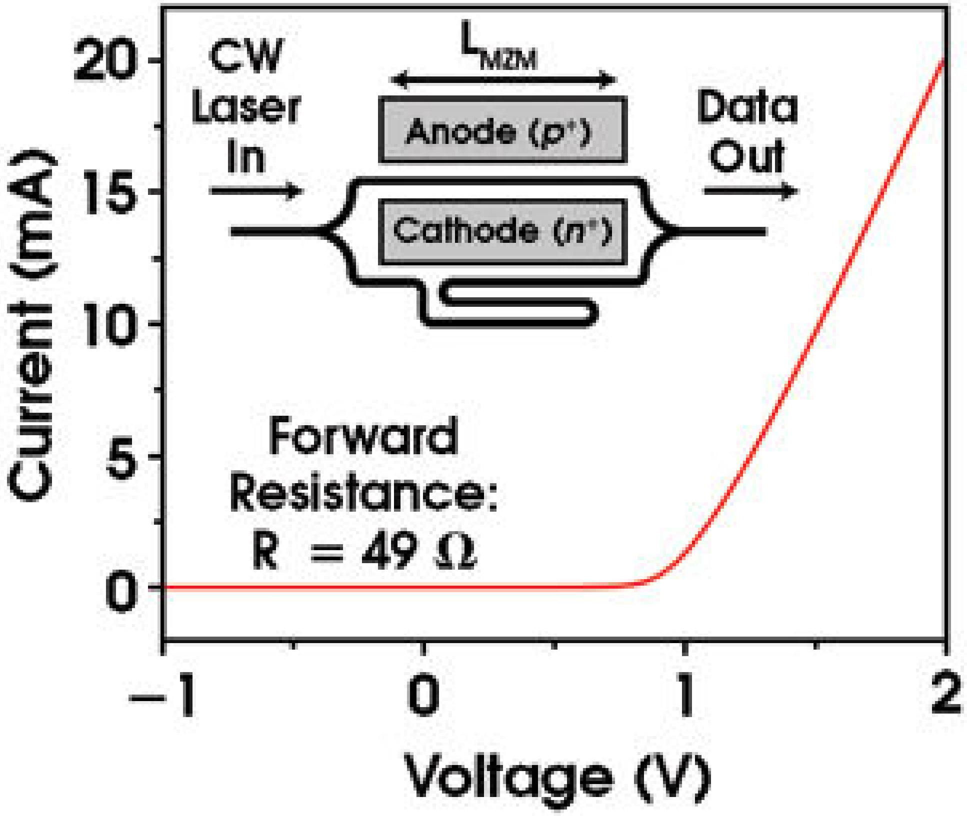
1V p-p AC, 1.6V bias

Light pipes into chip seem to be polymer – not rad-hard

But other people do similar things with forms of Si, SiO2, etc

IBM


p+
i
n+
220 nm
550 nm
35 nm
Box
200 nm


CW
Laser
In
L_MZM
Anode (p+)
Cathode (n+)
Data
Out
Forward
Resistance:
R = 49 Ω
Current (mA)
Voltage (V)
20
15
10
5
0
−1
0
1
2

Modulating Lasers is inefficient compared to modulating light.
Also, much of the power can be moved out of the tracker

Power for Electro-Absorption Light Modulator :

MIT 50 uW at 1 Ghz, scales with F, 500 uW at 10 GHz ?

Drivers – not known, but driving low power devices

Power of Laser and Driver:

* **Lasermate VCSEL 850 nm**
  10 ma, 1.6 V = 16 mW for approx 300 u W light

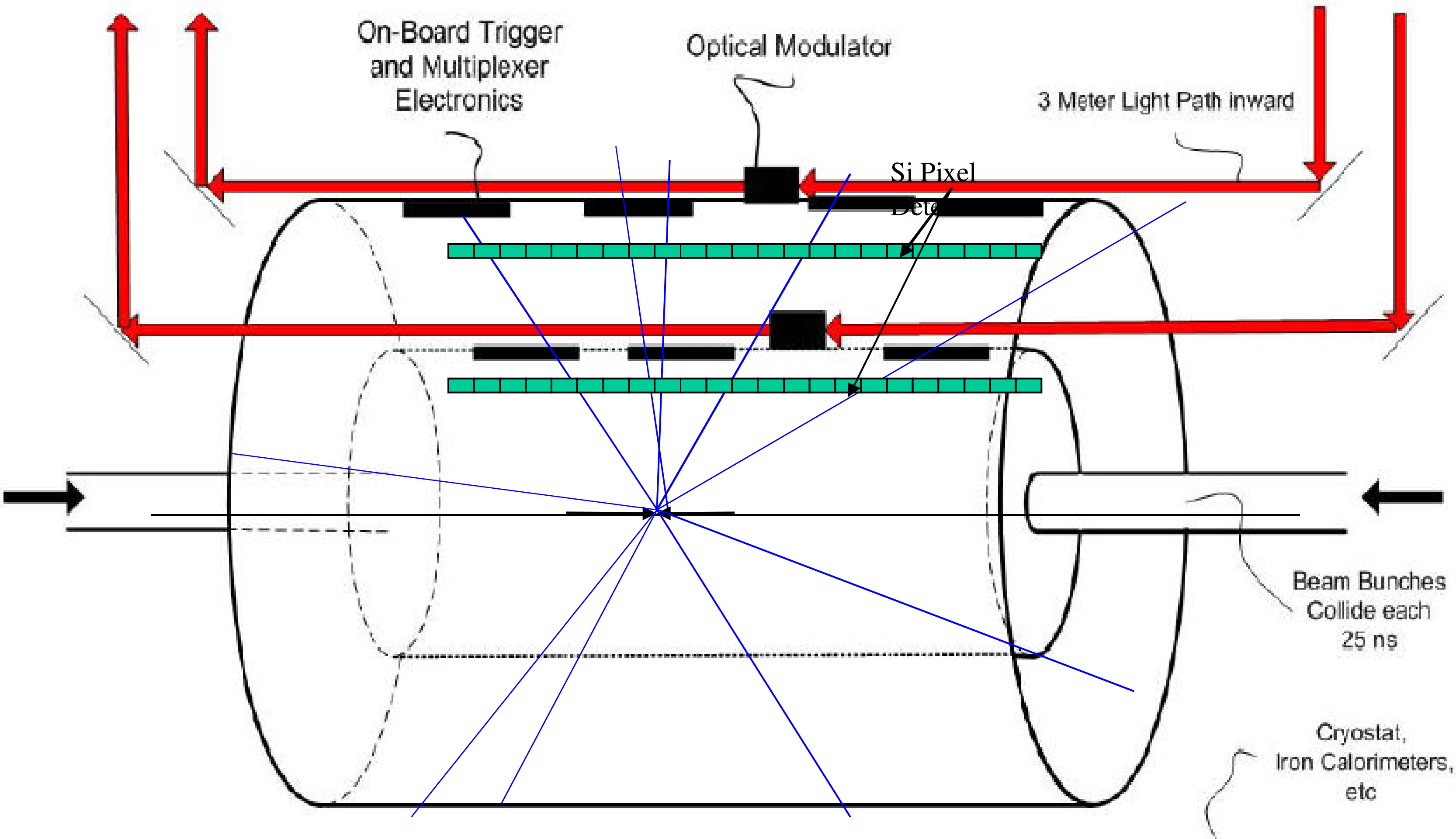
* **A 10 Gb driver for VCSEL is claimed to be very efficient at 45 mW**

Mechanics of Laser beams for Data Transmission and Triggering

- Steering of laser beams with feedback
- MEMS mirrors or Lenses

  needed at longer distances, ~meters

Schematic view of use of Modulators and Light Beams in a High Energy Colliding Beam Tracking Detector

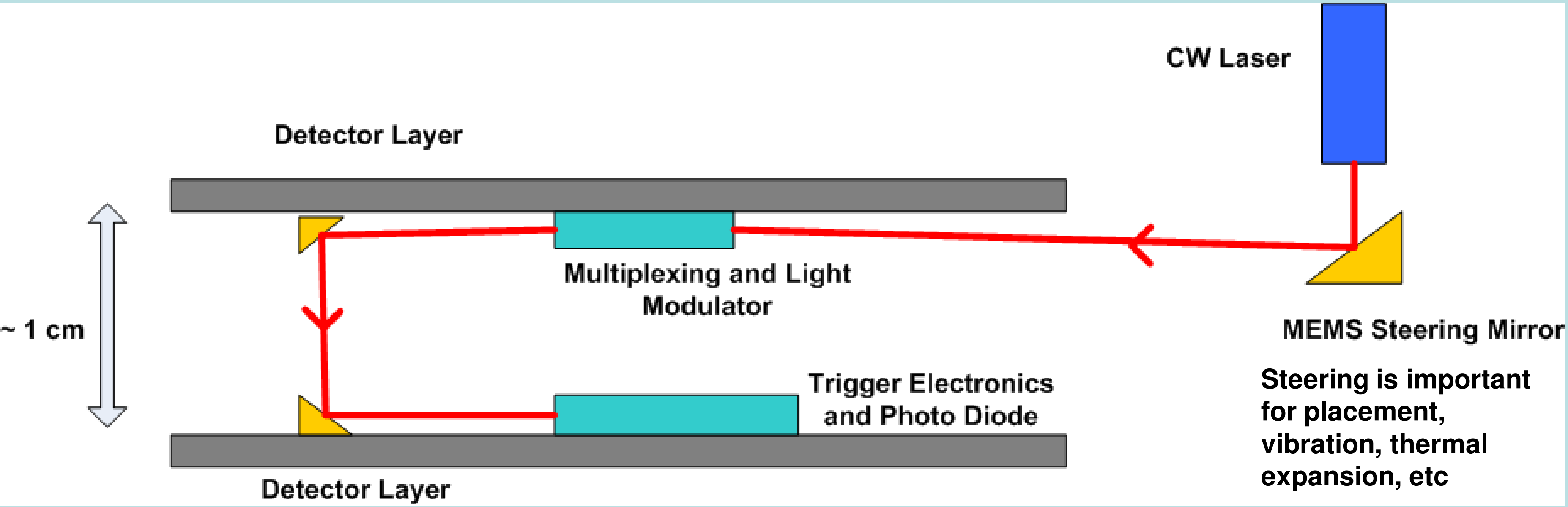


12 Tracking Cylinders, 10^7 Pixels, 1000 Optical paths

(down from 40000 fibers in existing CMS detector)

What is shown here is readout of data from tracker - but ….

Basic Triggering Data Flow



This is a way to get data from one layer to another

distances from ~ 3 mm up to cm

bandwidths per channel of 1 to 5 Gb.

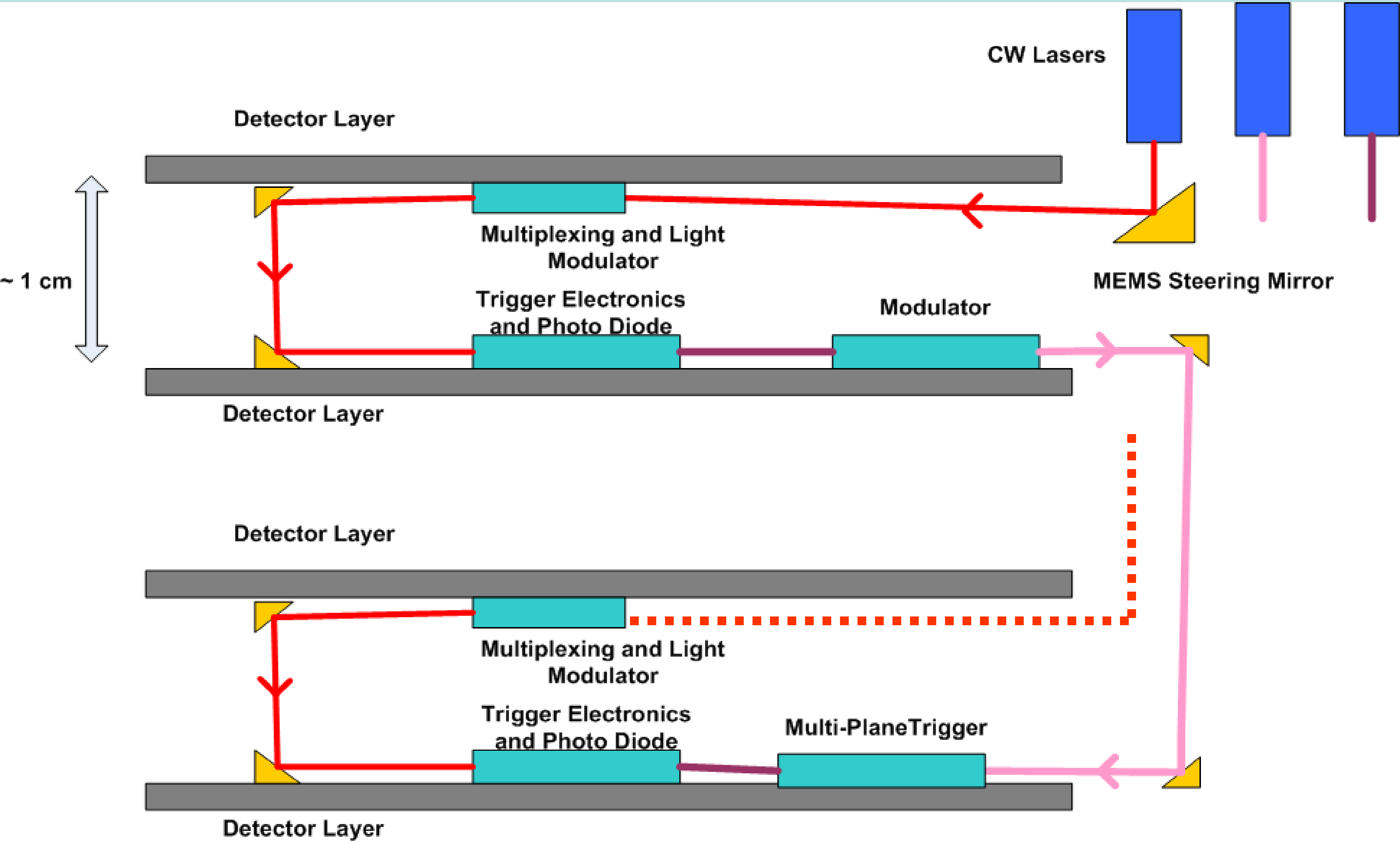
There could be many of these per pair of Staves

Data can be taken off detector in the same way (Not Shown Here)

Data Path for On-Board Trigger

All-Optical Multi Plane Trigger ?

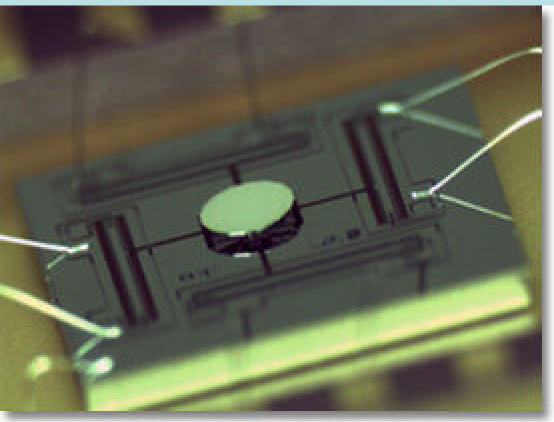
MEMS steering mirrors are very important for getting laser beams into device, and for routing data outside the staves.

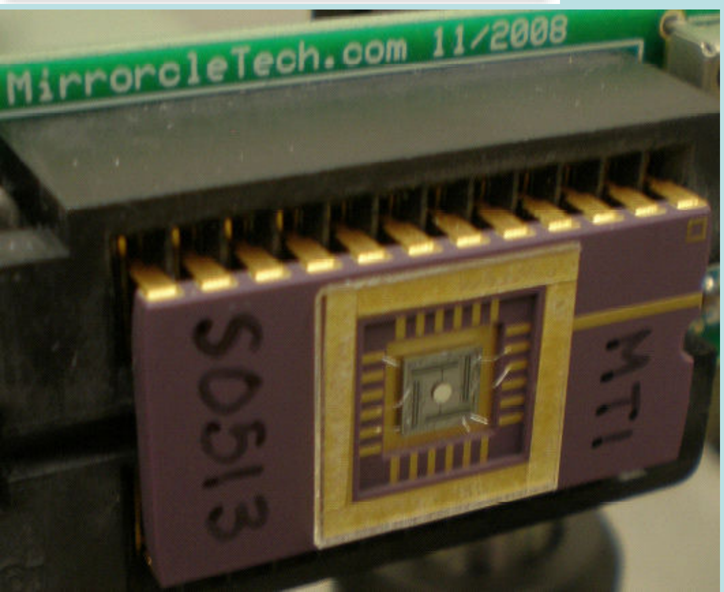


Again, Optical Data readout not shown

MEMS Mirrors and Lenses

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





The Lucent LambdaRouter: MEMS Technology of the Future Here Today

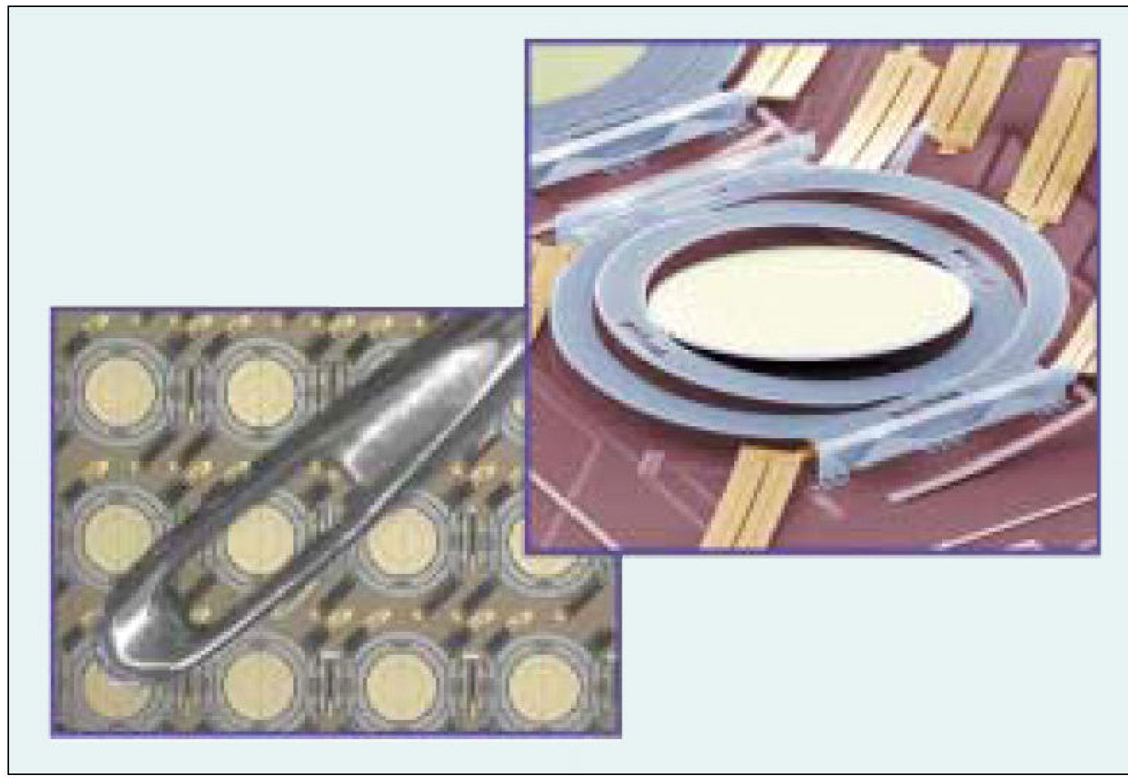


Figure 4. *Two images of MEMS-based OXC mirrors used in the Lucent LambdaRouter. The image in the upper right is a single mirror, and an array of mirrors is shown in the lower left. An eye of a needle is shown for comparison on the array.*

LBL-HP Approach

MEMS Lenses

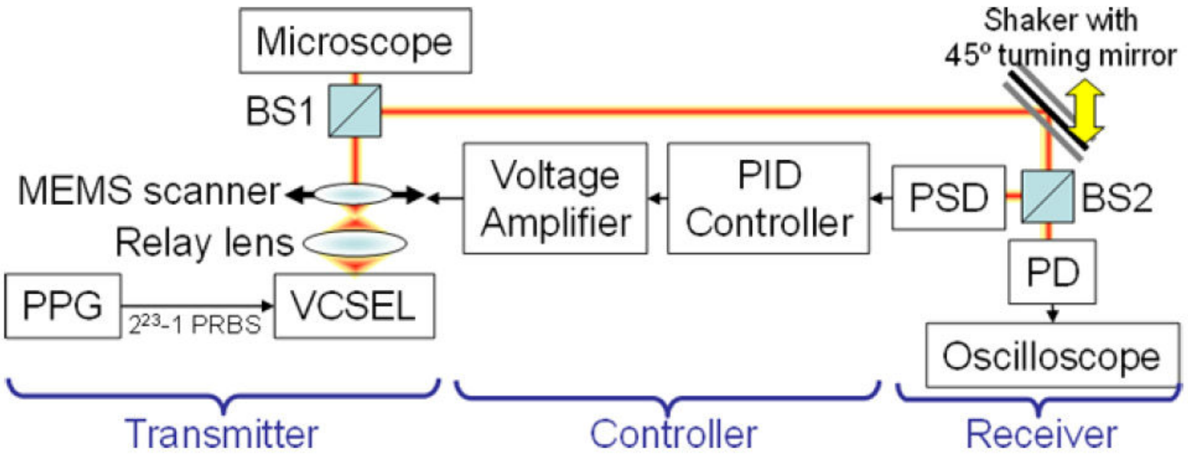
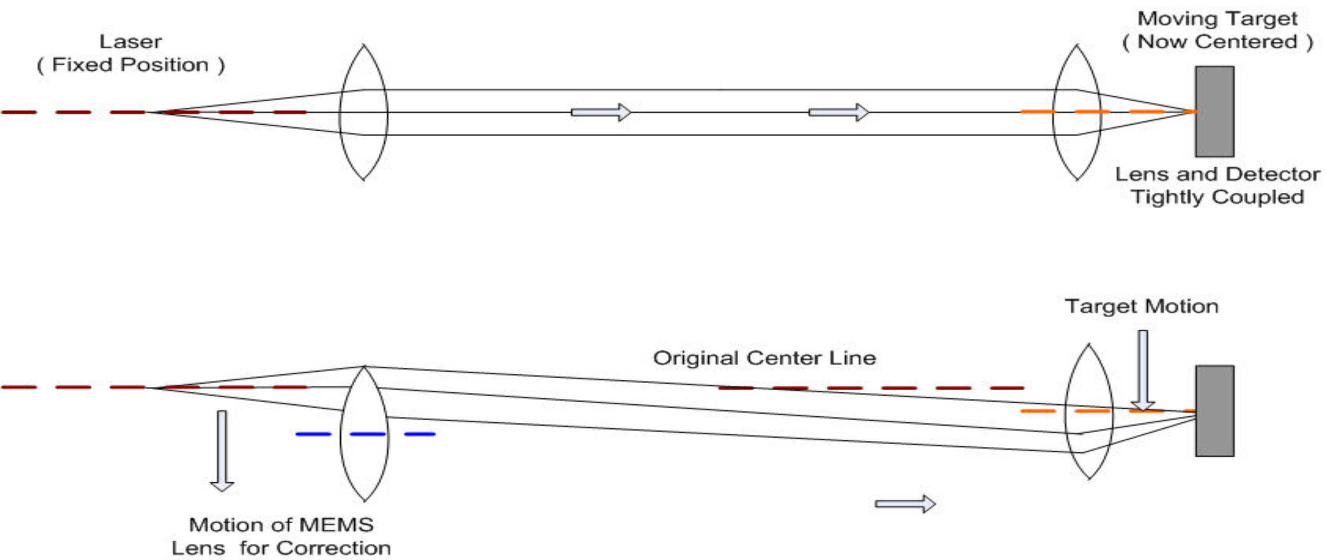
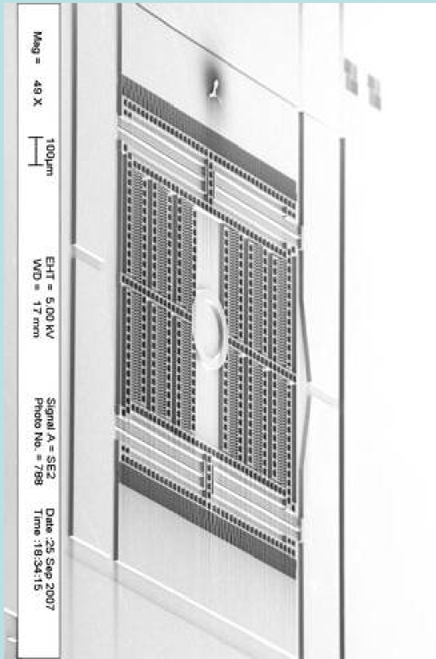


Fig. 11 Schematic diagram of our experiment setup with a mechanical shaker for real beam displacement. BS: Beam splitter. PPG: Pulse pattern generator at 1 Gbits/s. PD: high-speed photodetector with 1 GHz 3-dB bandwidth

Schematic of LBL MEMS Lens Steering
(Very schematic)





Coupling

- Between Tracking Layers –
  ..Short distances between layers and relative stability allows use of simple mirrors (gold plated silicon)

- Some kind of focusing is needed in and out of modulator and photodetector if these are small, integrated into CMOS
- Size of features in Silicon is < wavelength of light in air.
- There is ongoing work on these issues:
  .. Silicon, SiO_2 light pipes,
  .. Radar-horn like with index gradient
  .. Holographic lenses

Holographic Lens: One Example of getting Light into a Chip

C. Gunn, Luxtera Inc.

10 Gb/s CMOS photonics technology

Interfacing silicon waveguides to SMF is traditionally expensive, involving optical lenses, die edge preparation and alignment tolerances <<1μm. A holographic lens (HL) allows light to exit/enter the die normal to the surface of the die. As shown in Figure 2, a fiber is brought near the die surface, illuminating the HL, which consists of diffractive optical elements etched in to the silicon. The light is turned 90° and simultaneously focused into the silicon waveguide. This process is efficient with less than 1.5dB loss over most of the optical C-band (1530 to 1570nm).

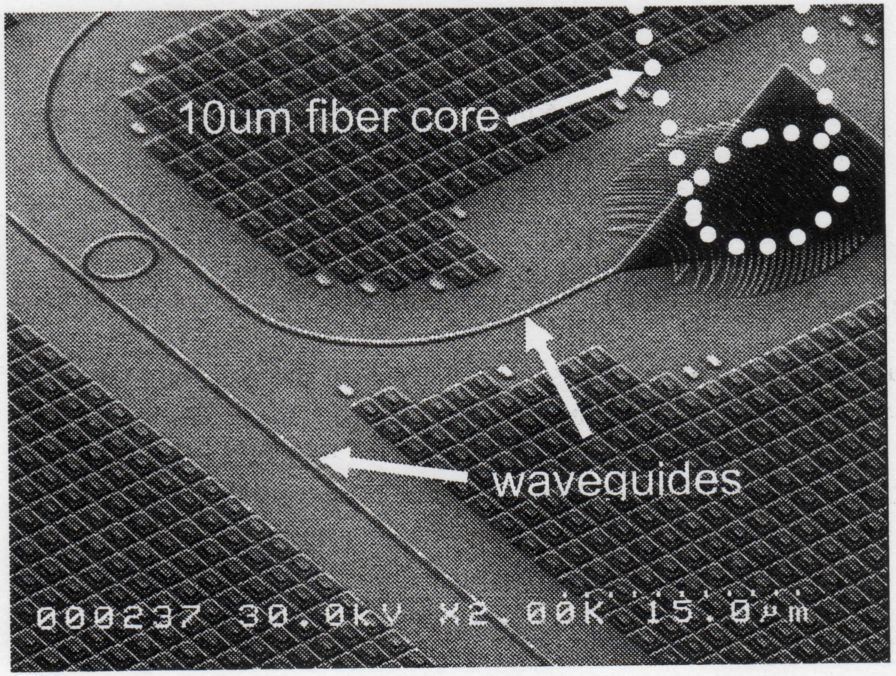
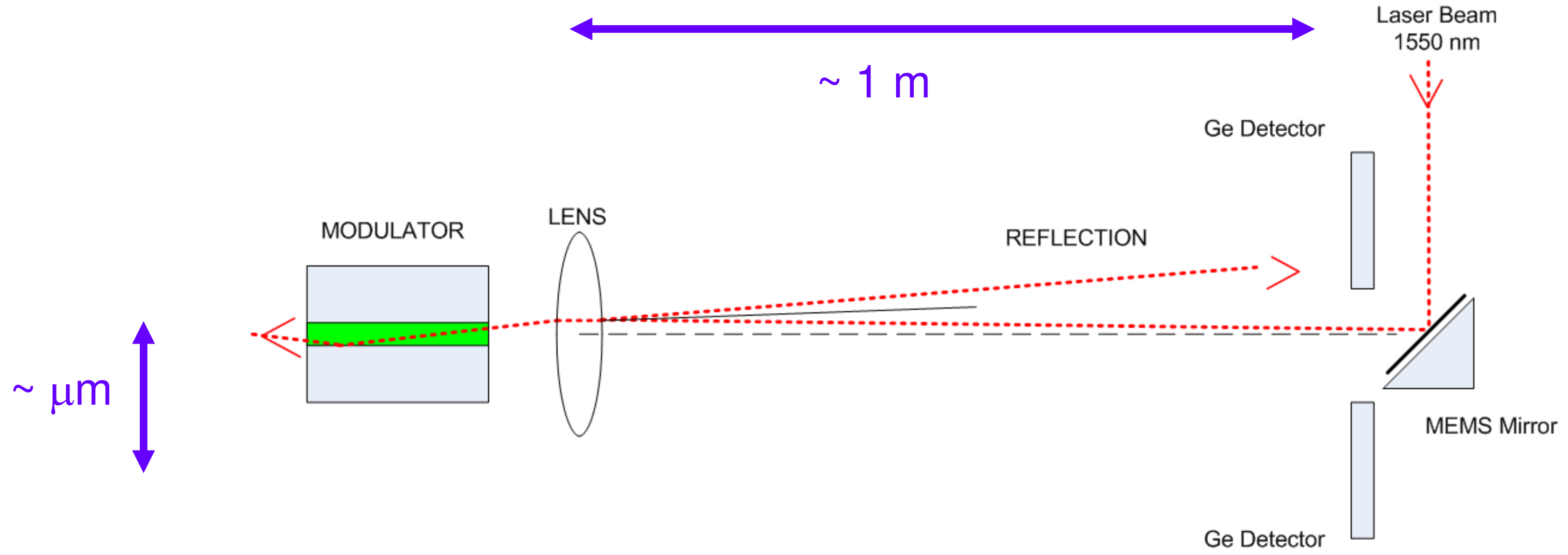
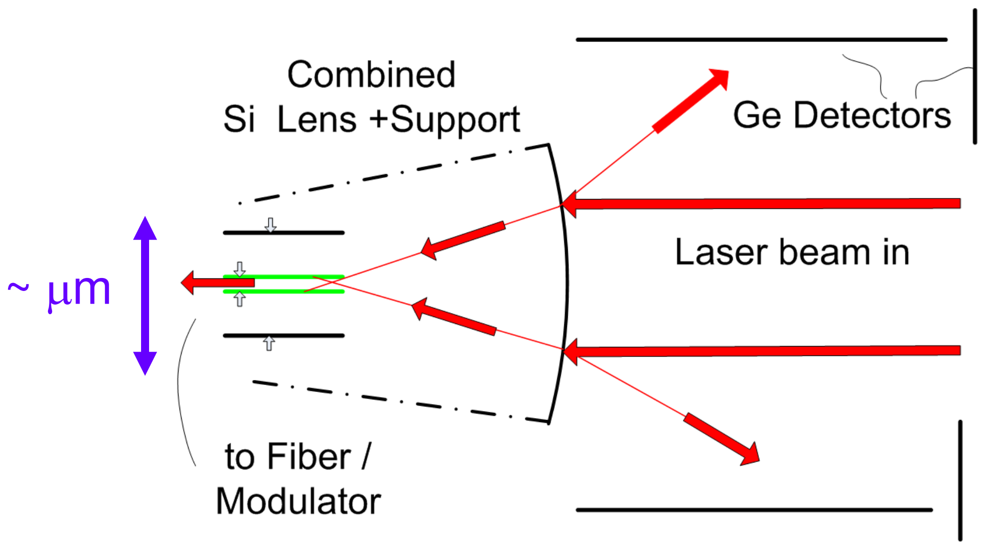


Figure 2. SEM photograph of a holographic lens (upper right corner) illuminated by an optical fiber (represented by dashed lines). Light is coupled into the submicron waveguides shown.

Our ideas for the link to test in MC and in Hardware





A Basic Issue is the data path for the Feedback loop.

We Are trying to integrate the optical coupling with the Feedback.

Radiation Hardness of SiGe

ATLAS Pixel Upgrade Expects :

~30 Mrad (small pixels), ~8.4 Mrad (long strips)

Some studies:

- **ATLAS SiGe Transistor bipolar study**
  .. tests at 10, 25, 50 Mrad and 2x10^15 neutron/cm^2
  .. Degraded, but working at highest doses

- **Cressler SiGe HBT (heterojunction bipolar transistors)**
  .. 5x10^13 proton (63 MeV) / cm^2 =6.7 Mrad for Space
  .. no problem

- **MIT-Argonne SiGe Photo Reflectance (related to Photo Absorption)**
  .. 3 x 10^16 and 3x10^17 electrons (3MeV) /cm^2
  .. (~ 700 to 7000 Mrad , but no nuclear displacement)
  .. Degraded, but should work at highest doses

Report on

MIT SiGe material irradiated at

Argonne 3 MeV Van deGraaf

Photoreflectance (PR) of GeSi after Electron Radiation

Jifeng Liu MIT

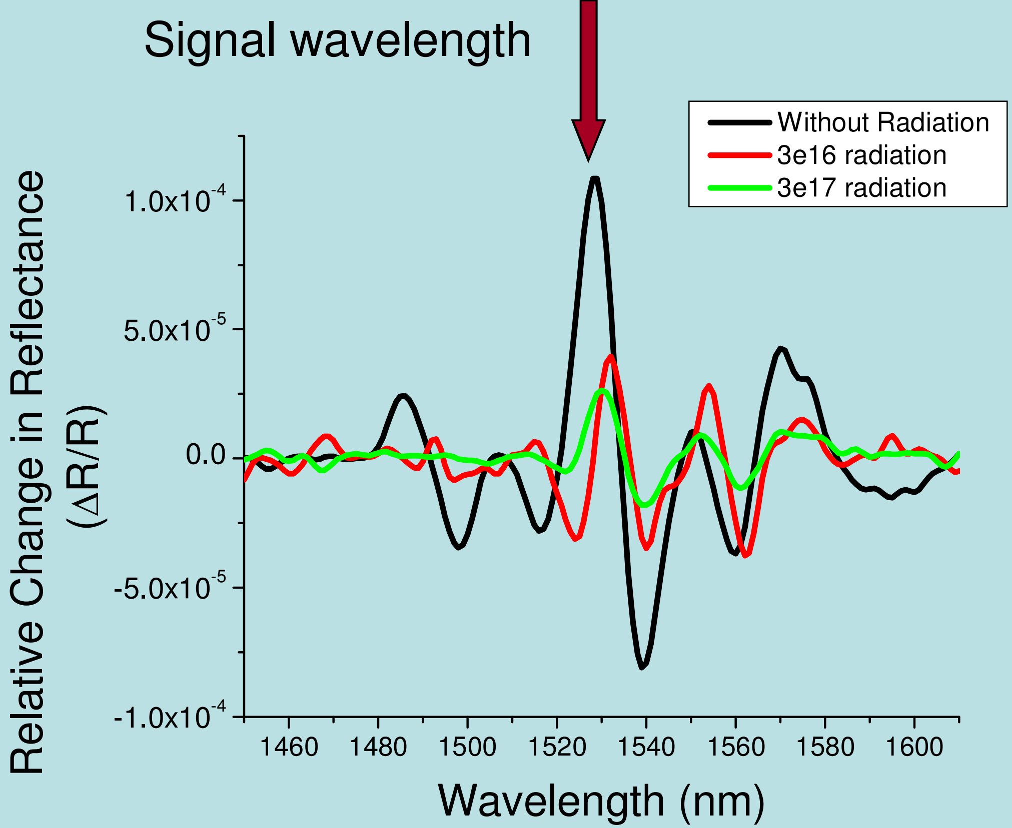
GeSi 2 cm x 2 cm

Thin layer of Ge mixing stresses Si Matrix

Look at Reflectance of GeSi at Operational wavelength ~1550 nm

Use another laser, 480 nm, to generate Electric field similar to what would be used inside Modulator

Results



- All samples from the same wafer. For the radiated samples, several positions near the center (radiation region) were tested and we show the ones with the lowest PR signals here to be conservative

- PR oscillation amplitude decreased by 2.5x after 3e16/cm^2 radiation, and by ~4x after 3e17/cm^2 radiation. Most likely due to radiation generated defects that reduces the carrier life time in the Ge material, and subsequently, the # of carriers generated by the 488 nm laser to modulate the electric field.

Discussion

- Change in electric field upon laser illumination is approximately proportional to the # of photogenerated carriers at steady state, or inversely proportional to the carrier life time.
- Therefore, after 3e17 electrons/cm^2 radiation the carrier lifetime is decreased by ~4x due to radiation defects.
- The dark current is likely to increase by several times due to the reduction in carrier lifetime judging from the PR result. However, usually it will not affect the modulation depth since the counter electric field due to carrier generation in the depletion region is still much lower than the applied field (>60 kV/cm) for electroabsorption modulators. As a result, it is very likely that the modulator is still operational but the dark current is increased.

A Different Topic – Optical Processing for Track Finding

A) Tracks with R-Phi plotted in x-y plane are straight lines with slope = momentum

B) Optical image by Lens is a 2D Fourier transform at the Focus

C) Data is input to 2D Spatial Modulator

D) Optical Fourier image recognition is known to work (railroad tracks, text, etc)

E) Proposed at Snowmass 1986, Technology was too slow and clumsy

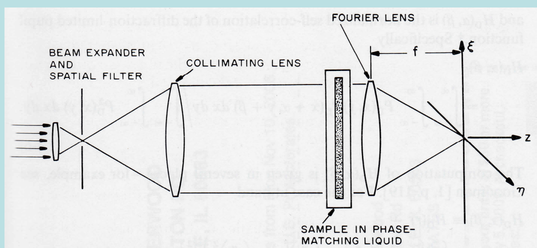
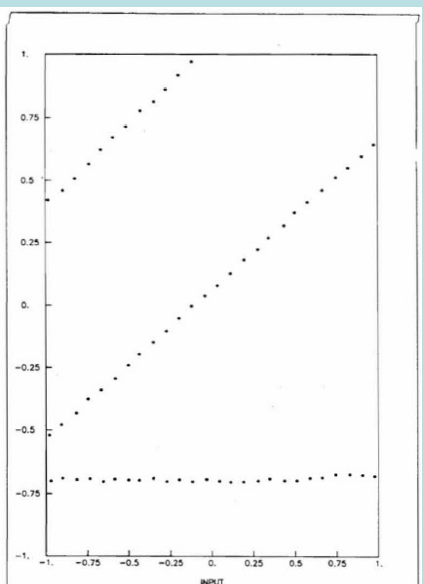
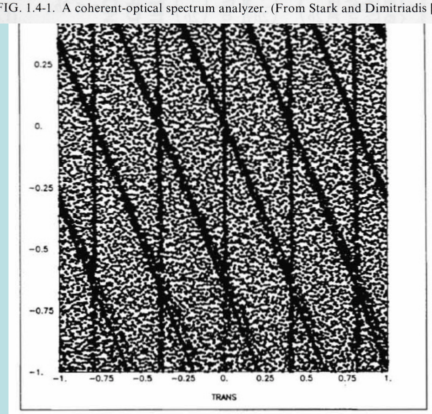


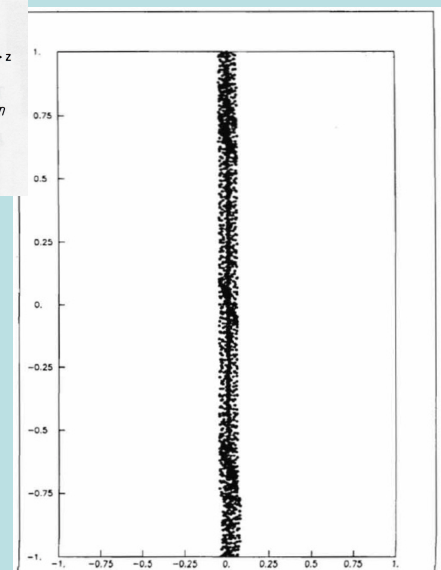
FIG. 1.4-1. A coherent-optical spectrum analyzer. (From Stark and Dimitriadis [10].)



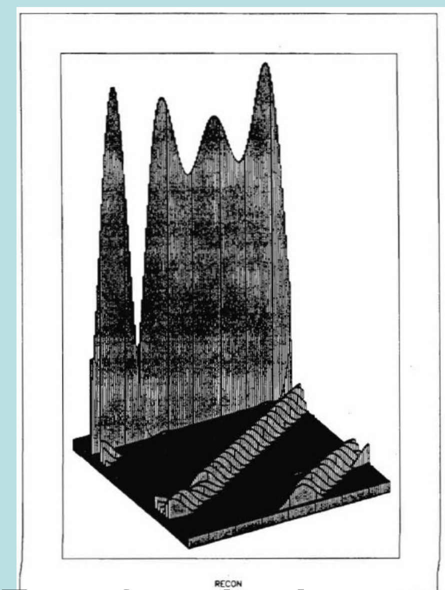
Track hits plotted in R-Phi, ~Horiz. = High Mom.



2D Fourier Transform



Output of Filter (Slit)



Transform back to R-Phi

Conclusions

- Optical Modulators and beams in air would allow low mass, high speed data links between tracking layers for an onboard Trigger.
- The new technologies would also be good for no-fiber, no copper readout from a tracker.
- The MIT microphotonics center has broad experience in optics and is interested in working with HEP

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“The Lucent LambdaRouter”, D.J.Bishop, et al, IEEE Communications Magazine, 0163-6804/02/

Robust free space board-to-board optical interconnect with closed loop MEMS tracking

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Free-space optical links for board-to-board interconnects

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(1) HP Labs, Hewlett Packard, 1501 Page Mill Road, Palo Alto, CA 94304, USA,
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