Optical Links Based on Silicon Optical Bench Technology for High Energy Physics Applications

Vega Wave Systems

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Vega Wave Systems, Inc.

- Five employees, 2 PhDs
- SBIRs: 2 Phase IIs (MDA, NASA) and one Phase I (DOE)
- Facilities: 5000 sf with1500 sf of Class 1000 clean room
- Full semiconductor device fabrication, packaging and test (DC-50GHz).
- Capabilities: semiconductor laser diodes, detectors, RF devices & circuits, silicon optical bench, fiber amplifiers, optical transceiver design.

Collaboration with FNAL

- Collaborators
  - Simon Kwan
  - Alan Prosser
  - Ron Lipton
  - Ray Yarema
  - Ted Liu
  - Jim Hoff
  - Gregory Deptuch
  - John Chramowicz

Optical Links Based on Silicon Optical Bench Technology: Outline

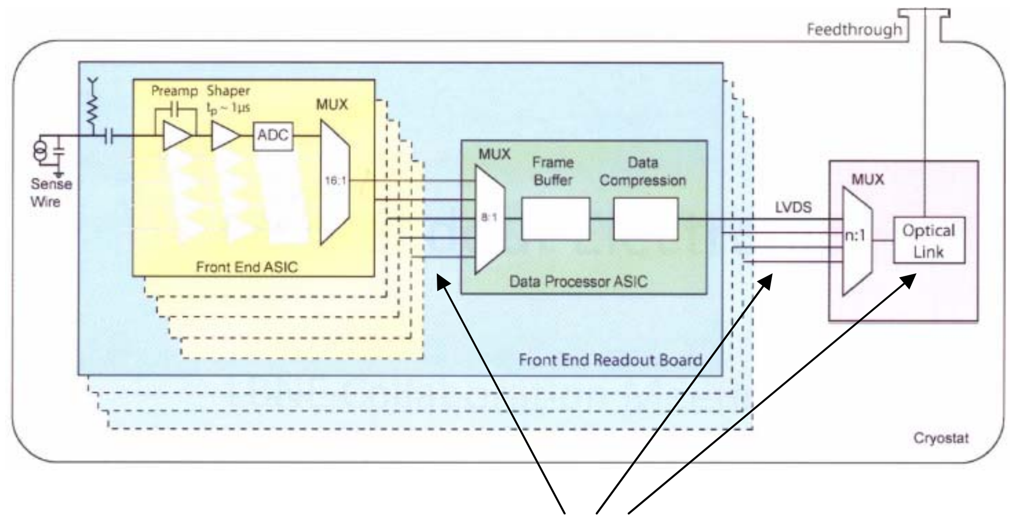
- Future HEP Applications of Optical Links: The Need
  - Problems with current optical link implementations
    - Silicon-detector based
      - LHC, SLHC, ILC, CLIC and Multi-TeV Muon Collider
    - Liquid Argon TPC
- Solutions
  - Cableless Readout using Free-Space Optics
  - 3D integration of optical links with sensors and electronics
  - Silicon optical bench technology

Future HEP Applications of Optical Links: The Need

- Form a set of standardized solutions
  - Instead of new set of optical links for each new experiment
  - Toolbox of solutions new designs can utilize
    - Save time, money and effort
    - Solutions tailor-made for HEP
- LHC, SLHC, ILC, CLIC and Multi-TeV Muon Collider
  - Require silicon detectors capable of reconstructing charged particle trajectories
  - Imposes stringent demands on the data links
    - High-speed transfer the data from the silicon detectors to the data acquisition system
    - Large number of silicon detectors / massive amount of data
    - Requires the use of fiber optic links.
  - Methods to increase the density and speed of these links and to reduce the number of fiber ports are needed

Future HEP Applications of Optical Links: The Need (continued)

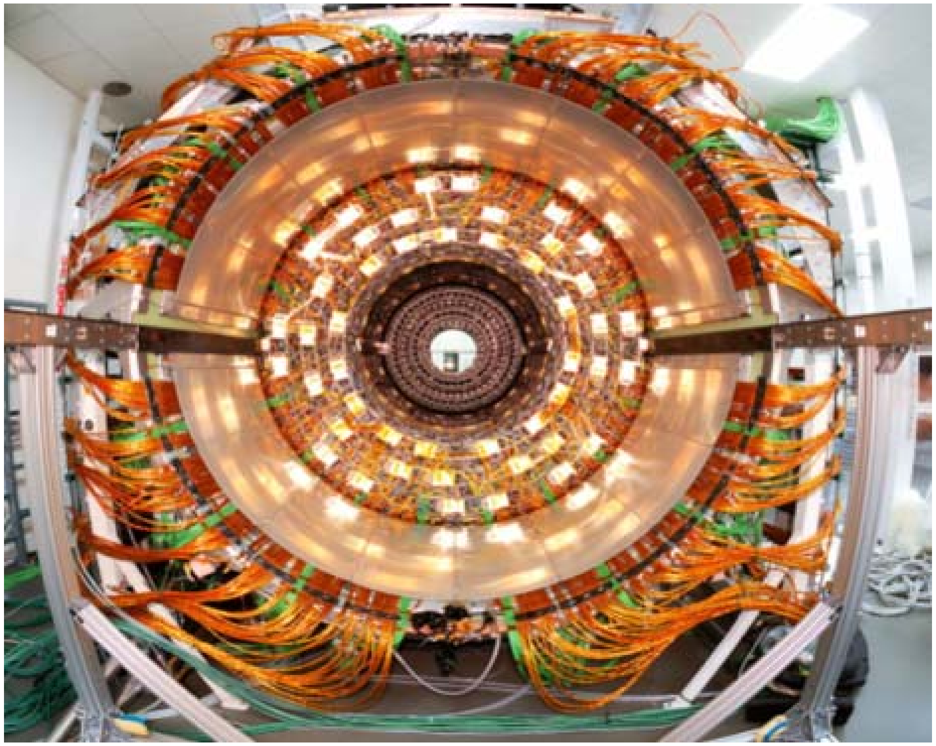
- Very Large Liquid Ar TPC:
  - Highly multiplexed detector readout electronics within the cryostat
    - Reduce the number of cables penetrating the cryostat wall.
  - Aggregation of the readout electronics requires high speed links to send the data outside the cryostat
    - Higher link data rates result in fewer cables and cable penetrations
    - Data rates of ~1 Gb/s and higher perform better with optical links
    - Decision not made yet whether to use optical links
  - Critical requirements:
    - >20 year lifetime
    - Operation at 93˚K
      - Electronics reliability issue
    - Low power
    - Low outgassing
    - Low radiation environment
    - Low EMF



Possible Optical Link Usage

Future HEP Applications of Optical Links - The Problem: Multi-Million Channels

- Example: CMS Tracker
  - Massive number of links, wiring, and optical cabling
    - Need to reduce the amount of cabling
  - >40,000 optical links
  - High radiation environment
    - 100 kGy
  - Data moves both radially and axially



Cross section photograph of the CMS silicon tracker

Future HEP Applications of Optical Links - The Problem: Multi-Million Channels (cont.)

- CMS Tracker composed of:
  - Pixel detector
    - ~40 million pixels
  - Silicon strip tracker
    - ~10 million strips
    - Readout
      - Time-multiplexed 256:1
      - Over ~40,000 analog links
      - 40 MSamples/s
      - 50-100m fiber lengths (SMF-28)
  - Digital control
    - ~2,500 digital links
    - 40 Mb/s
  - Transmitters
    - Four 1310nm InP FP laser diodes
    - Mounted on separate silicon v-groove submounts
    - Passively aligned to single mode fiber

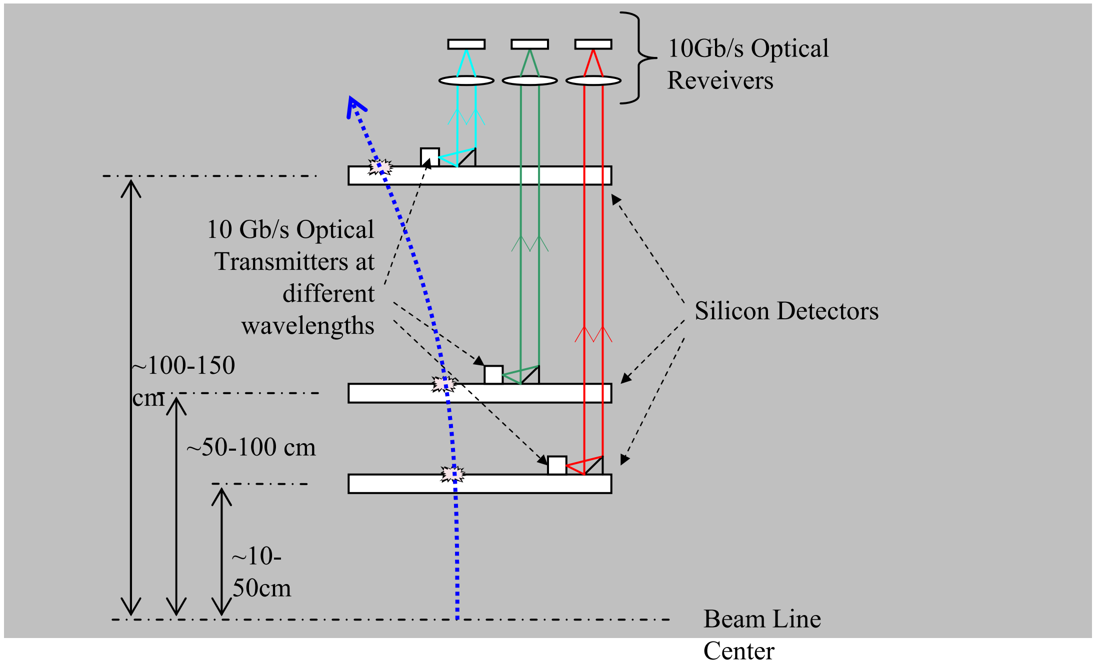
- Radiation Hardness Assurance
  - Initial reliability
    - 28 samples
    - 100kGy exposure (equivalent worst-case radiation exposure expected inside CMS)
    - Followed by aging at 80ºC for 2500 hours
      - Equivalent to operating 10 years at room emperature
    - No failures observed
      - Extrapolates to a 5mA threshold shift and 5% efficiency loss after 10 years of irradiation
- Advanced Validation Testing
  - Wafer qualification
    - 30 devices randomly selected
    - Irradiated at 100kGy
    - Aged at 80ºC for 1000hrs
    - Wafer passes if devices 95% pass
      - Drive current < laser driver max current

Future HEP Applications of Optical Links – Proposed Approaches

- Free space optical links for cableless readout between silicon detector layers (radial)
- 3D integration of high speed optical links (10Gb/s) with electronics
- Utilize proven technologies
  - InP lasers
  - Silicon optical bench
  - SMF-28 single mode commercial fiber

Free-Space Optical Interconnects for Cableless Readout Overview

- Large amounts of data required from silicon vertex detectors
  - Conventional solutions require large parallel or very high-speed serial data links
    - Cabling is cumbersome and physically impractical in large detector arrays.
- Free-space optical links for trigger and data extraction could alleviate this situation
  - Long wavelength (λ= 1.3 or 1.5μm) InP-based transmitters
- Novelty and feasibility of free-space optical links
  - Silicon is transparent to the infrared wavelengths of the free-space optical data link
  - Fiber optic cabling to connect layers is eliminated



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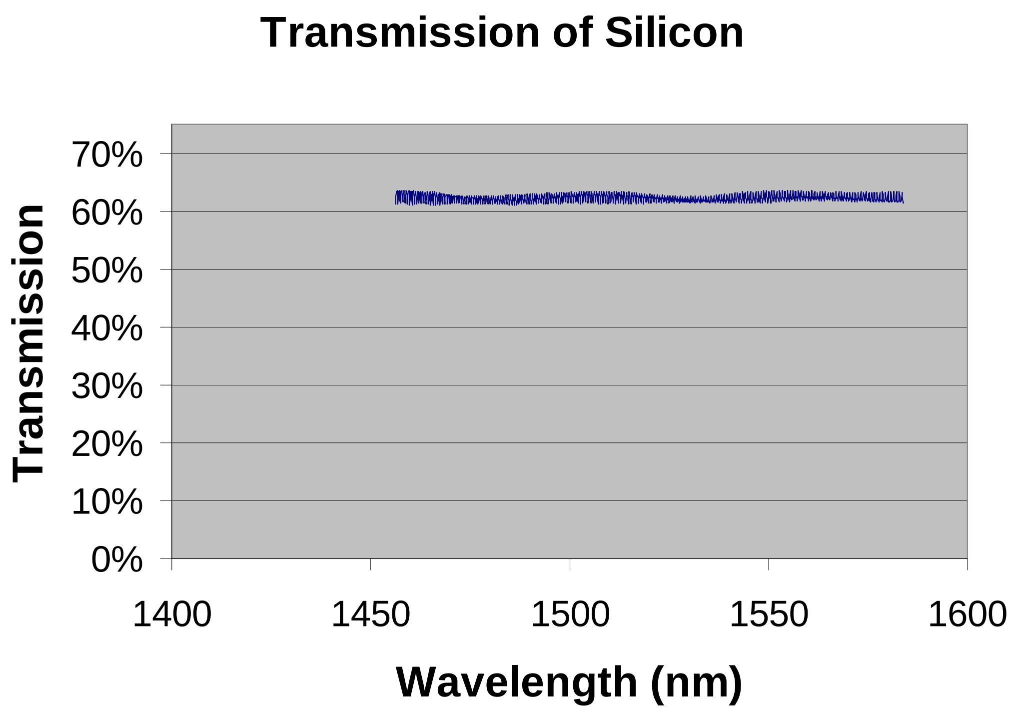
Free-Space Optical Interconnects for Cableless Readout

Optical Transmission in Silicon

- Optical properties of silicon
  - Indirect semiconductor with band edge 1.12 eV
    - Transparent to $\lambda > 1100$nm
  - Refractive index n~3.5
    - Transmittance (undoped Si)

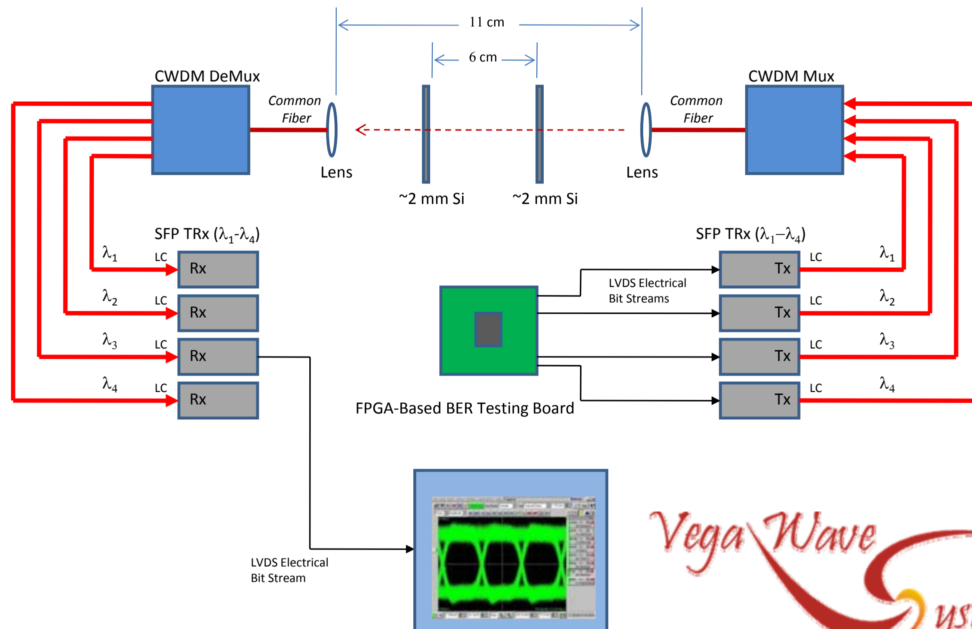
$$T = 1 - \left(\frac{n-1}{n+1}\right)^2 \sim 69\%$$

    - Can be increased even further with anti-reflection coatings
    - Transmission through Hamamatsu silicon detector
      - Occluding metal
      - Need window



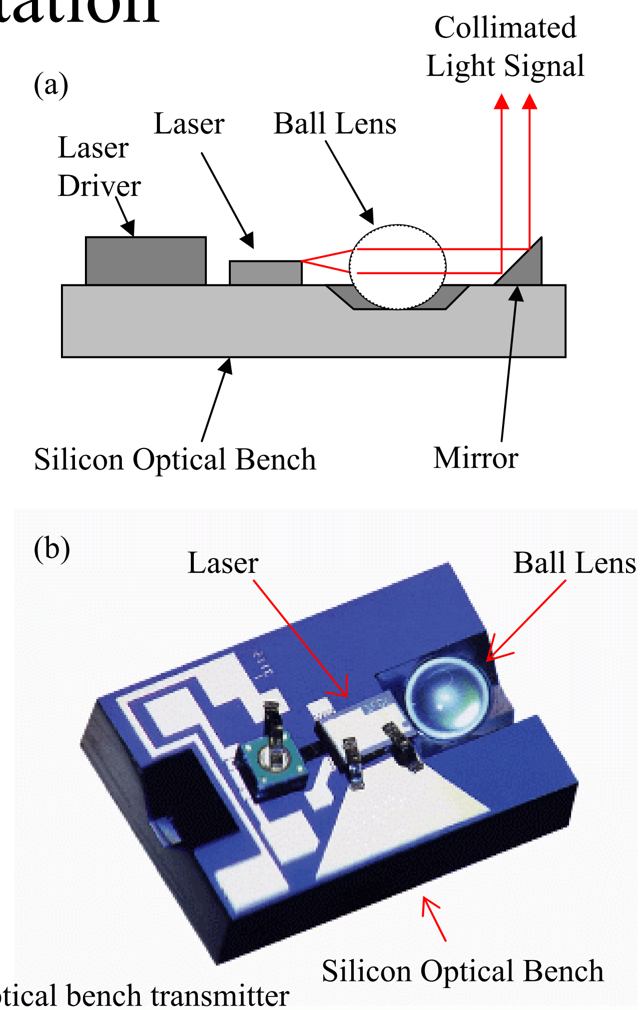
Free-Space Optical Interconnects for Cableless Readout
Preliminary Feasibility Experiments

- Free-space demonstration setup
  - Collaboration with FNAL
    - Simon Kwan, Alan Prosser, John Chramowicz
  - Vega Wave Systems
    - Provided and set up free-space optical hardware
    - Transmission measurements
  - FNAL
    - Provided high-speed transceivers and test equipment
    - High-speed testing
  - Successful demonstrations
    - Single 10Gb/s link at 1310nm
    - 4 CWDM links ~1470-1550nm
      - Simultaneous transmission
      - 1Gb/s
    - 4mm if silicon
      - Equivalent to 12 layers of Hamamatsu silicon detectors



Free-Space Optical Interconnects for Cableless Readout
Possible Implementation

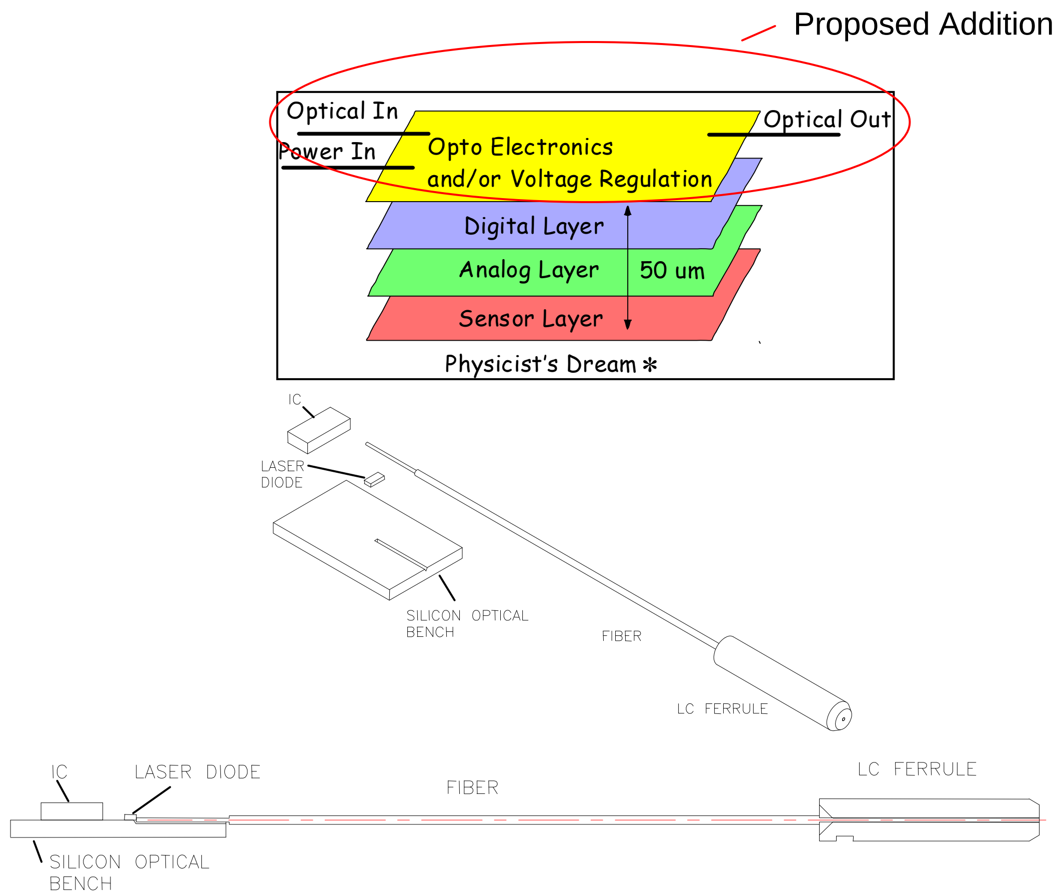
- Approach:
  - Edge-emitting lasers and lenses mounted on silicon optical bench
- Technology is commercially proven
- Silicon optical bench technology and InP lasers
  - Utilized in CMS tracker
  - Rad-hard reliability proven
    - 100 kGy



(a) Possible custom silicon optical bench transmitter assembly for free-space optical link for cableless readout. (b) Commercial transmitter assembly based on silicon optical bench technology by Lucent Technologies as part of their Laser 2000 program.

3D integration of optical links: Overview

- Miniature transmitter
  - InP laser
  - Passively aligned to fiber optic cable using silicon optical bench
- Silicon optical bench
  - Hybridized onto 3D electronic stack via die-to-wafer bonding
  - Awarded SBIR to investigate / develop this process
- In Collaboration with FNAL



(Top) conceptual sketch of a physicist's dream for 3D integration of sensor, electronics, optoelectronics and fiber optics. (Middle, Bottom) Our approach to the optoelectronic / fiber portion of 3D integration is to utilize a silicon optical bench, which, in turn, is integrated onto the 3D electronic integrated circuit (IC).

* Sketch from Ron Lipton, FNAL

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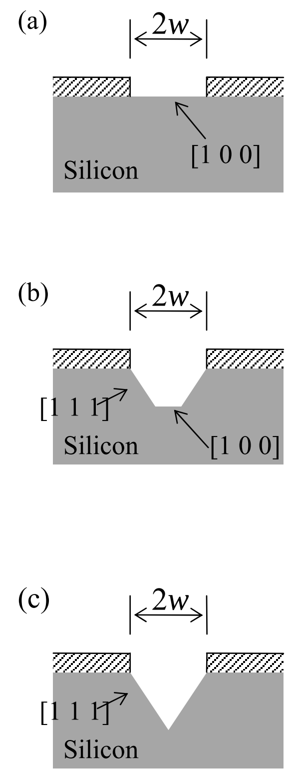
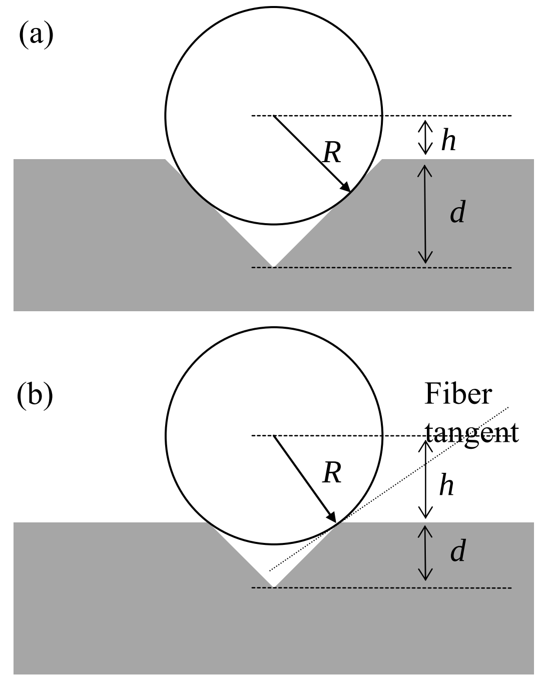
Silicon Optical Bench Technology Overview

- Precision v-grooves micro-machined into silicon
  - Start with [1 0 0]-oriented silicon with silicon nitride coating
  - Open a slot within the silicon nitride using standard photolithography and etching
  - Use a selective KOH etch at ~80C to etch silicon
    - Highly anisotropic – etches [1 0 0] plane ~100x faster than [1 1 1] plane



Silicon Optical Bench Technology Overview (continued)

- Optical alignment
  - Can control depth / width of groove to micron accuracy
    - Sufficient for passive alignment of lasers to optical fiber
  - Alignment of InP edge-emitting lasers to optical fiber
    - Use flip chip technology
    - Emission location known to better than 0.1µm from surface of p-contact
      - Epitaxially grown



$$w=\begin{cases}\dfrac{R-h\sin\alpha}{\cos\alpha}, & h\geq R\sin\alpha\\ \sqrt{R^2-h^2}, & h\leq R\sin\alpha\end{cases}$$

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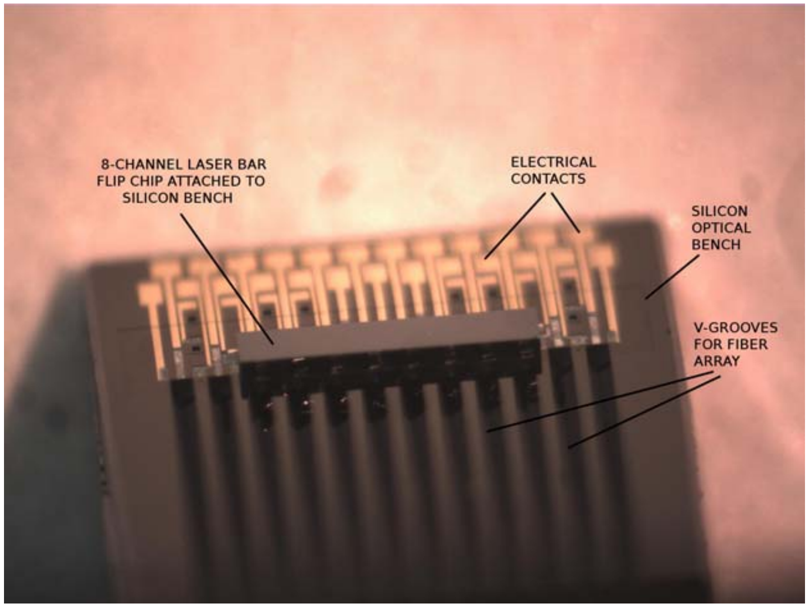
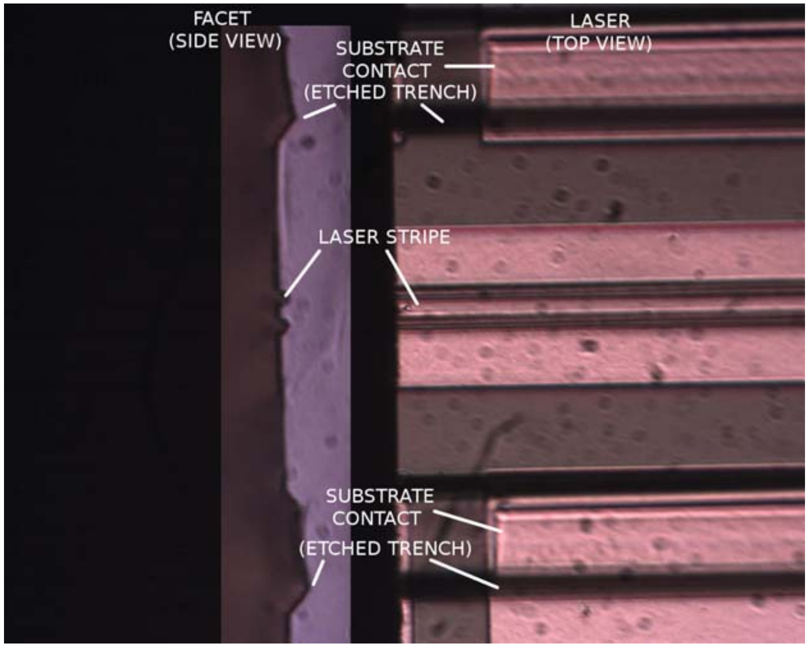
Silicon Optical Bench Examples

Laser Array flip-chip mounted on silicon v-groove



Laser Array



Side View of Facet

Top View

Summary

- Reviewed Applications of Optical Links for HEP Experiments
- Proposed Potential Solutions
  - Free space optical links for cableless readout between silicon detector layers (radial)
  - 3D integration of high speed optical links (10Gb/s) with electronics
  - Utilize proven technologies
    - InP lasers
    - Silicon optical bench
    - SMF-28 commercial fiber

Conclusion / Final Remarks

- The HEP community can clearly benefit from optical links for a variety of experiments.
- The needs of the HEP are unique: need non-standard (i.e. non-telecom) reliability testing, power consumption, environmental, and maintenance requirements.
- Current designs have used off-the-shelf parts where possible, but assembled in customized systems with communication protocols and reliability standards developed for each unique experiment. (i.e. the links/systems are custom designs for each experiment).
- We believe that the HEP community would benefit greatly from a set of standardized optical communication links from which they could pick and choose for new HEP experimental designs.
- These links could be developed to meet a standard range of power consumption, reliability, data-rates, form-factors and communication protocols.
- The HEP community could then draw from these standard qualified links in order design future experiments and save large amounts of both time and $.
- Forums/workshops such as this are a great first step to defining this type of standard for the HEP community.