Initial Results of Prototyping a 3-D Integrated Intra-Chip Free-Space Optical Interconnect

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Challenges for On-chip Optical Interconnect

- Signaling chain:
  - Efficient Si E/O modulators challenging
    - Inherently poor non-linear optoelectronic properties of Si
    - Resonator designs also non-ideal: e.g., e-beam lithography, temperature stability, insertion loss
  - Off-chip laser (expensive, impractical to power gate)
- Propagation medium:
  - In-plane waveguides add to the challenge and loss
    - Floor-planning, losses due to crossing, turning, and distance
  - Bandwidth density challenge
    - Density of in-plane wave guide limited
    - WDM: more stringent spectral requirements for devices and higher insertion losses, more expensive laser sources

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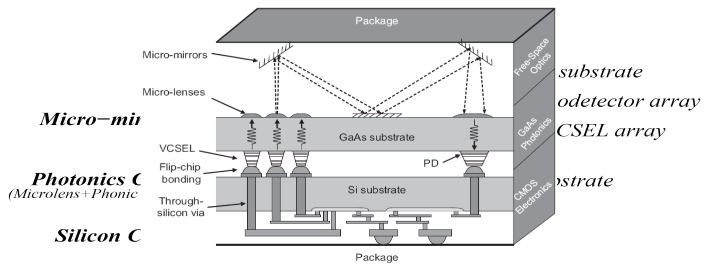
Free-Space Optical Interconnect: an Alternative



Side view (mirror-guided only)

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Advantages of Free-Space Optical Interconnect

- Signaling: mostly current (commercially available) technology
  - ✓ Large VCSEL arrays, high-density (movable) micro mirrors, high-speed modulators and PDs
  - ✓ Integrated VCSELs (Vertical Cavity Surface Emitting Laser) avoids the need for external laser and optical power distribution
  - – Disparate technology (e.g., GaAs)
- Propagation medium
  - ✓ Free-space: low propagation delay, low loss and low dispersion
  - – Hindering heat dissipation
- Networking
  - ✓ Direct communication: relay-free, low overhead, no network deadlock or the necessity to prevent it
  - ✓ Route virtual wires instead of packets
- New opportunities for system designers
  - ✓ Optimize communication (e.g. cache coherence protocol)

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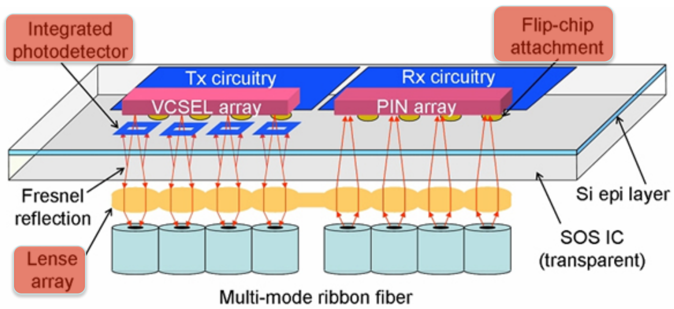
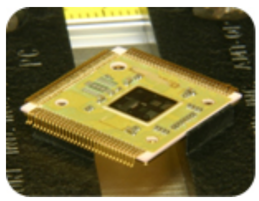
Commercially Available Tech.

Ultra Communications
Fiber optics for a harsh environment





IC with
- VCSELs
- PINs
- Photodetectors
- Micro-lenses

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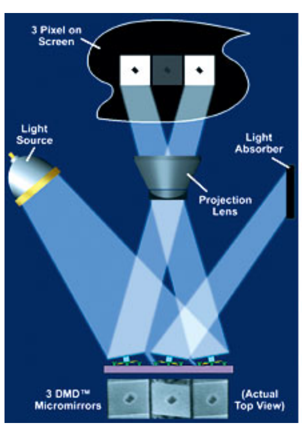
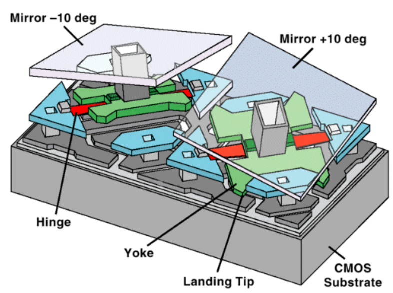
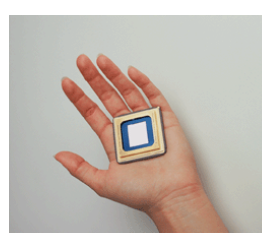
Digital Micromirror Devices by TI





Micro-Optical Electromechanical Device - MOEMS



900,000 microscopic mirrors

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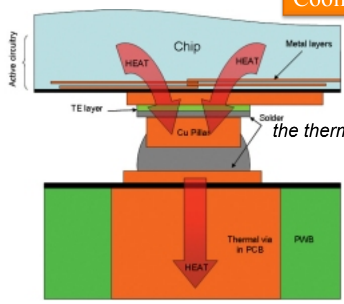
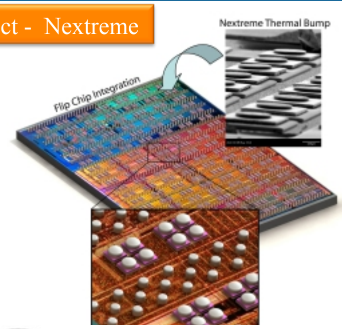
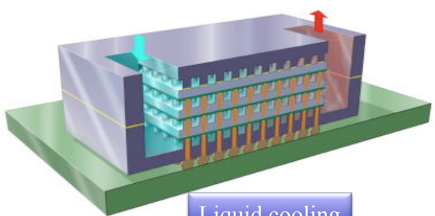
Challenges: Cooling Technologies

Cooling using peltier effect - Nextreme



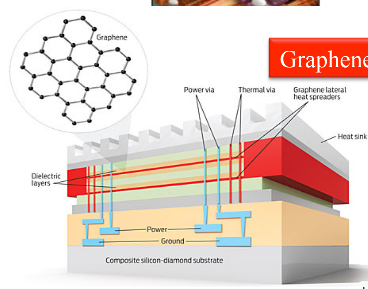
the thermal bump at work





Liquid cooling

Graphene



Prototype and Measurement Results

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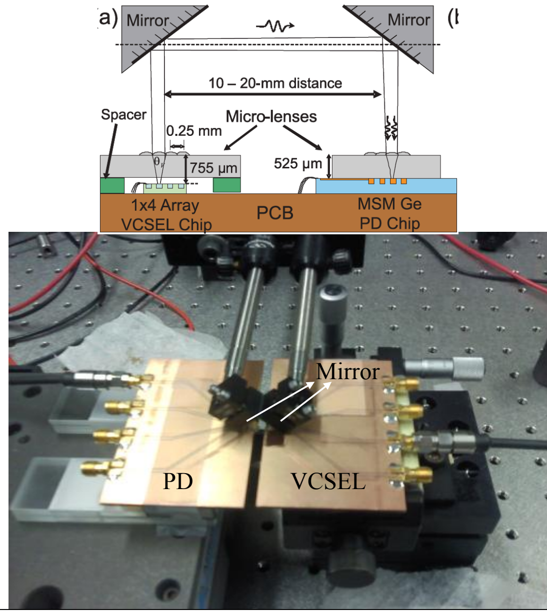
Link Demo on Board Level



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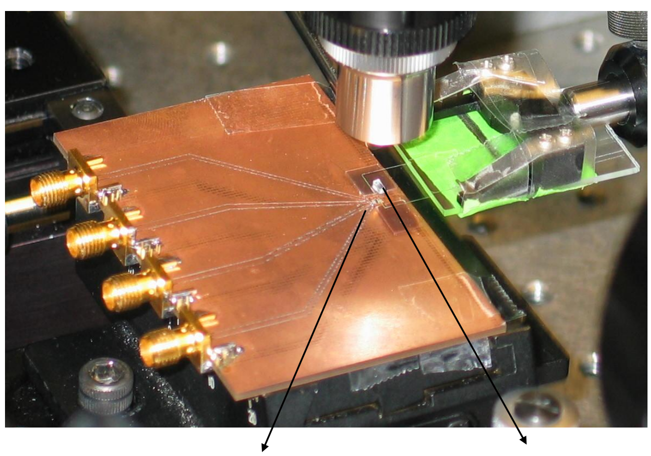
VCSEL and Microlense



Commercial VCSELs

Divergence: 30°
Speed: 10 Gb/s

Microlenses

Radius of curvature: 1.22 *mm*
Focal point: 730 μm

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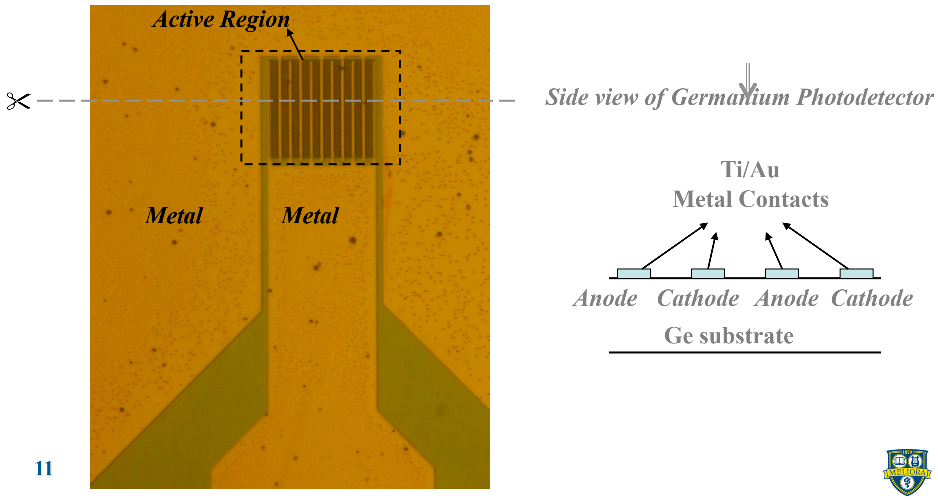
Germanium Photodetector

To appear in Photonics Technology Letters

Bandwidth: 13 GHz



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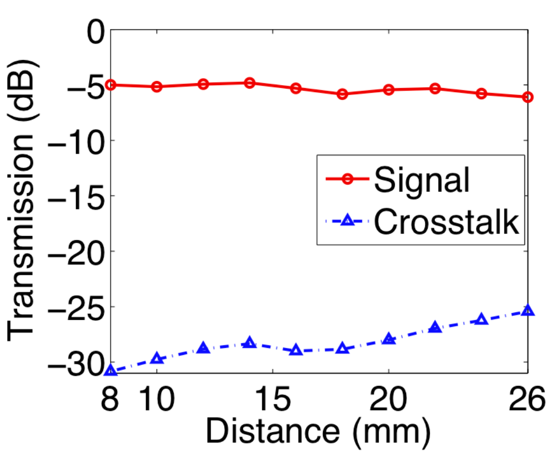
Transmission and Crosstalk



Optical path loss

- Expected = 2.5 dB
- Actual ≈ 6.5 dB

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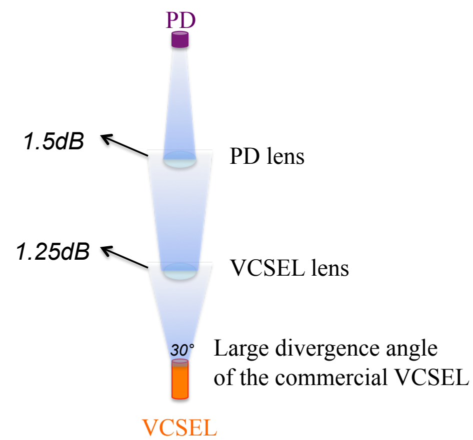
Transmission Losses Due to Beam Clipping



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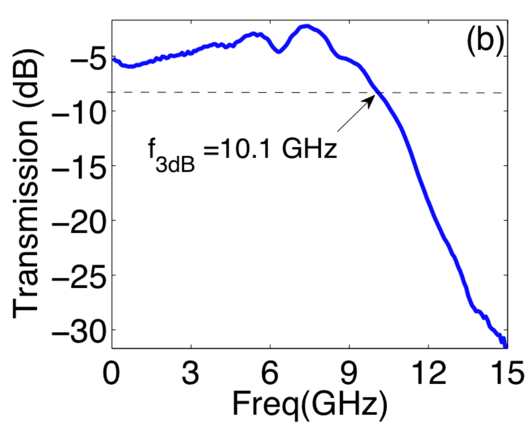
Small Signal Bandwidth at 1*cm*



Note: Small signal bandwidth does not change with distance

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Summary

- Fully-distributed free-space optical interconnect provides an alternative
- Technology readiness
  - Entire signaling chain is commercially available in large scale
  - 3D integration of disparate technologies common in small scale SoCs
  - Thermal issues may be avoided by piggybacking on other developments
- Initial prototyping results encouraging

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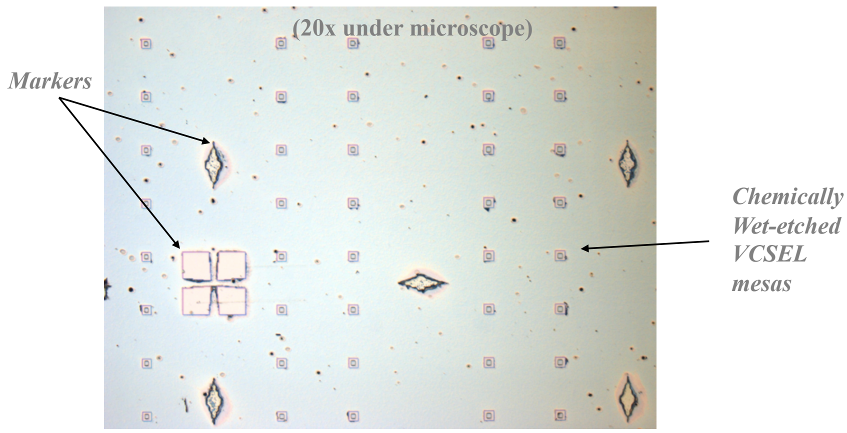
Prototype Custom-Made VCSEL Arrays



Photograph of VCSEL mesa structure

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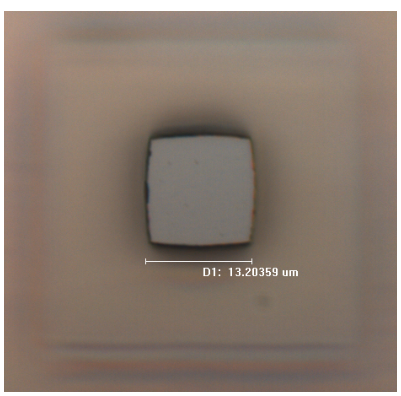
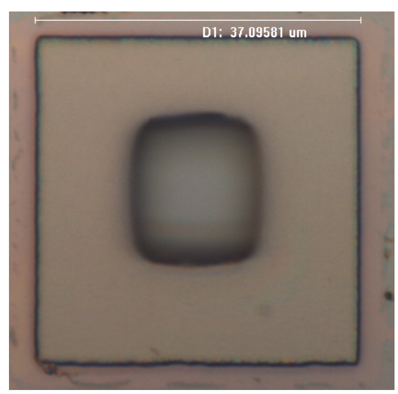
Single VCSEL Structure (Under Microscope)



a) Top view of the etched mirrors



b) The p-contact region of the VCSEL, located below the mirrors shown in a)

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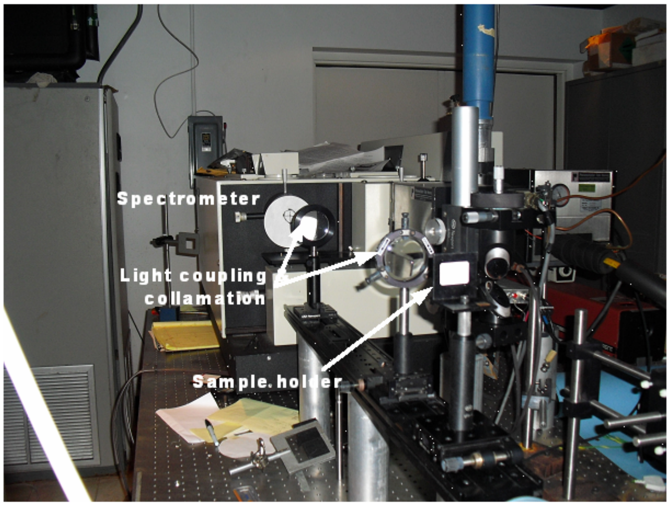
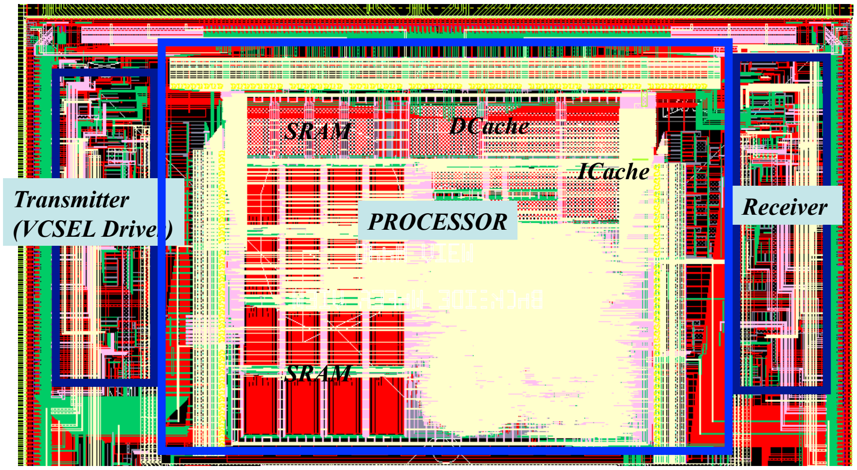
Spectrometer Setup

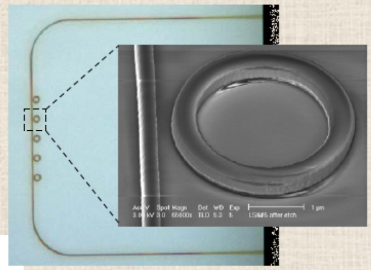


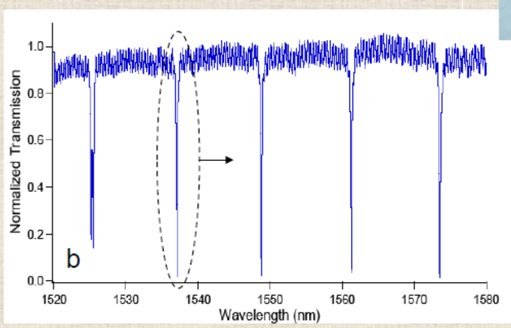
3D Test Chip for System-Level Demo

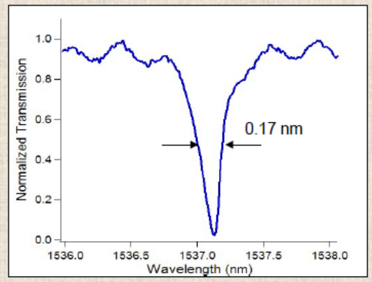


High-Q 1.5-µm-radius microring resonator

- Resonances from five cascaded microring resonators with slightly different radii ~ 1.5 µm
- High Q of 9,000 (BW ~ 20 GHz) and high extinction ratio of 16 dB.

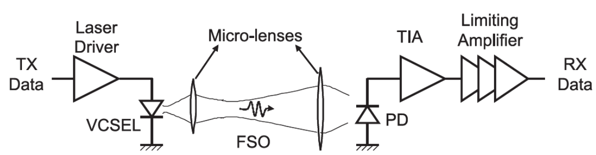






Q. Xu et al., *Opt. Express* **16**, 4309 (2008)

Efficient Optical Links



Free-Space Optics	
Transmission distance	2 cm
Optical wavelength	980 nm
Microlens aperture	90 μm @ transmitter, 190 μm @ receiver
Optical path loss	2.6 dB
Transmitter & Receiver	
VCSEL	aperture=5 μm, parasitic=235 Ω // 90 fF threshold=0.14 mA, extinction ratio=11:1
Laser driver	bandwidth=43 GHz
PD	responsivity=0.5 A/W, capacitance=100 fF
TIA & Limiting amp	bandwidth=36 GHz, gain=15000 V/A
Link	
Data rate	40 Gbps
Signal-to-noise ratio	7.5 dB
Bit-error-rate (BER)	10^{-10}
Cycle-to-cycle jitter	1.7 ps
Power Consumption	
Transmitter (active)	0.96 mW for VCSEL (0.48 mA@2V) 6.3 mW for laser driver
Transmitter (standby)	0.43 mW
Receiver	4.2 mW

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Related Work

- Buffer-less optical packet-switched network, Schacham and Bergman, *IEEE Micro* 2007
- Circuit-switched optical network, Schacham et al. NOC'07
- Bus or ring-based shared-medium optical interconnect
  - Ha and Pinkston *JPDC* 1997
  - HP Corona (Beausoleil *LEOS* 2008, Vantrease et al. ISCA'08)
  - Kirman et al. MICRO'06
- Free-space optics
  - Miller, *J. Sel. Top. in Quantum Elec*. 2007
  - Krishnamoorthy and Miller, *JPDC* 1997
  - Marchand et al. *JPDC* 1997
  - Walker et al. *Applied Optics* 1998

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