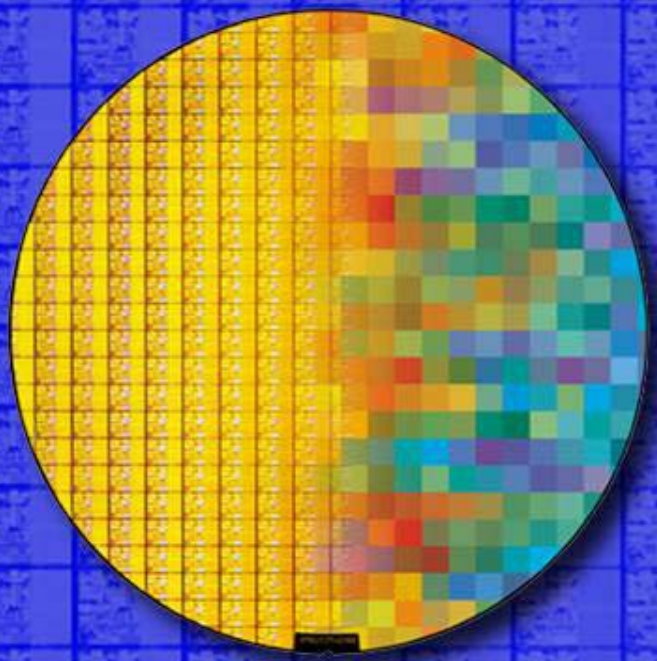
Silicon Integrated Photonics



Dr. Mario Paniccia,
Director Photonics Technology Lab
Intel Corporation

IEEE CAS Society
May 16, 2005

For More Info
http://www.intel.com/technology/silicon/sp/

Agenda

- Opportunity for Silicon Photonics
- Copper vs optical
- Recent advances
- Intel's SP Research
- Raman
  - amplification and lasing in Silicon
- Summary

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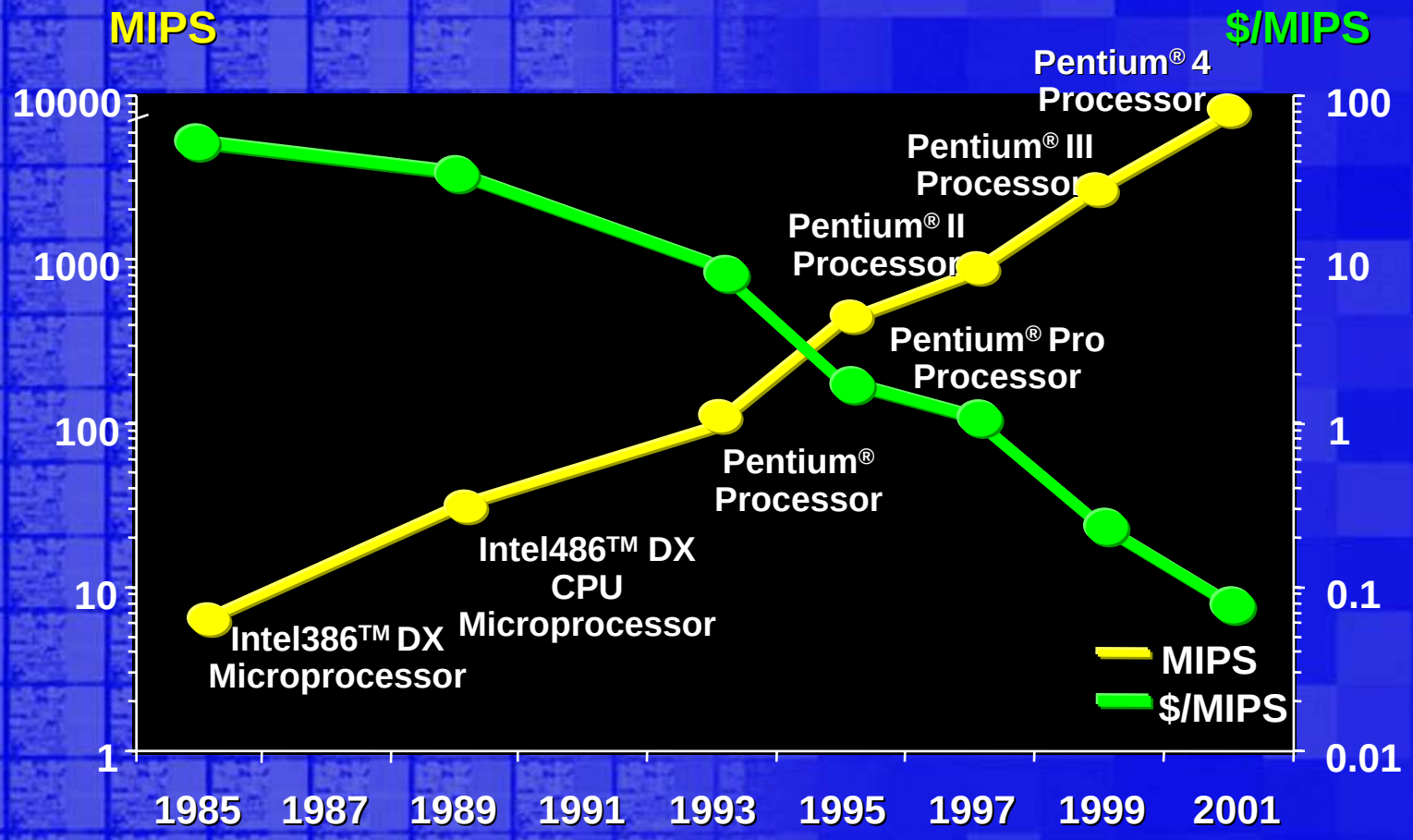
ELECTRONICS: Moore's Law Scaling



Integration & increased functionality

Volume economics – faster, better, cheaper

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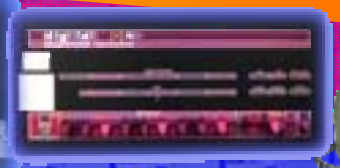
Extending and Expanding Moore's Law



Discrete SSI LSI VLSI

EXTENDING EXPANDING

Sensors

Mechanical

Biological

Fluidics

Wireless

Optical

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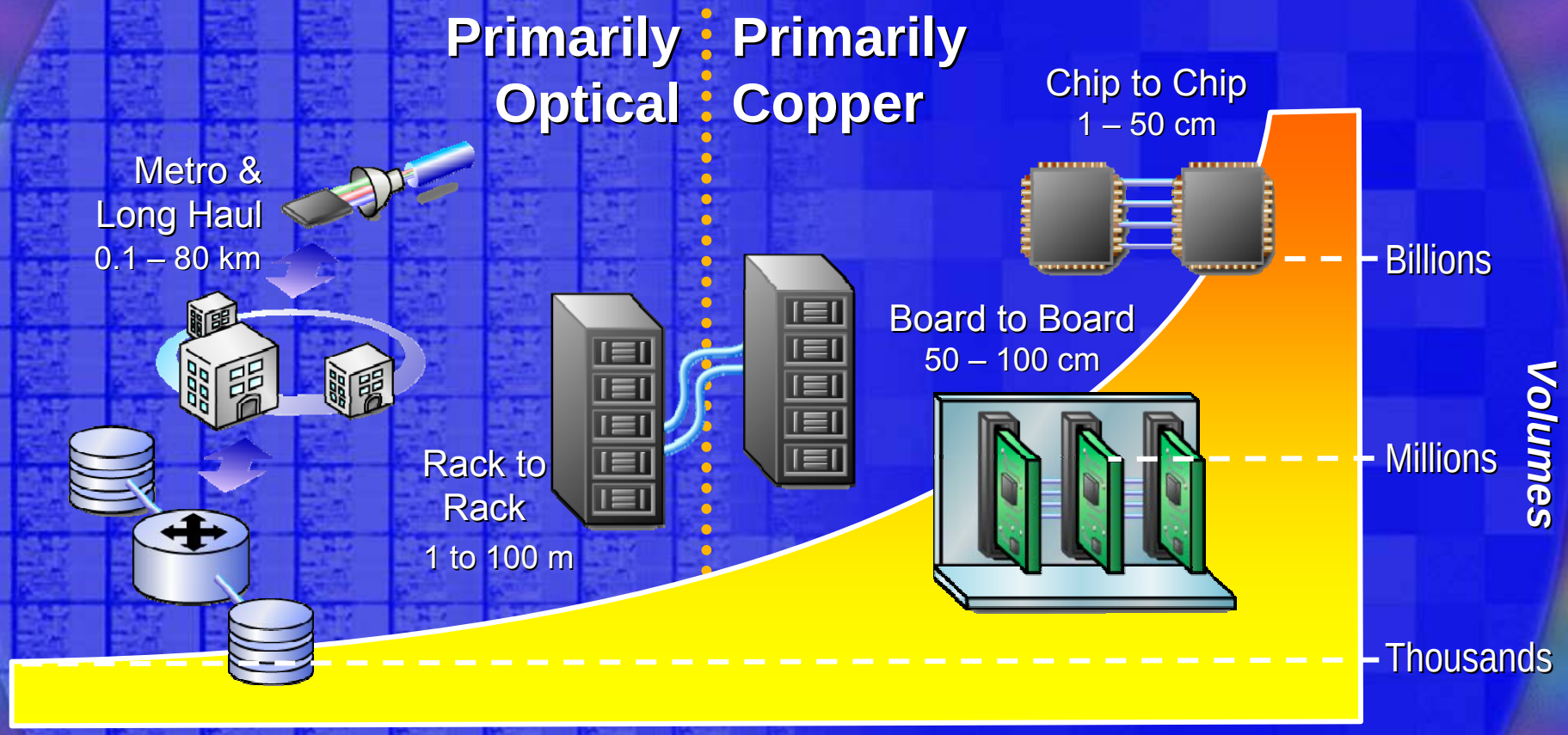
Today's High Speed Interconnects



Need to drive volume economics to drive optical closer to chip

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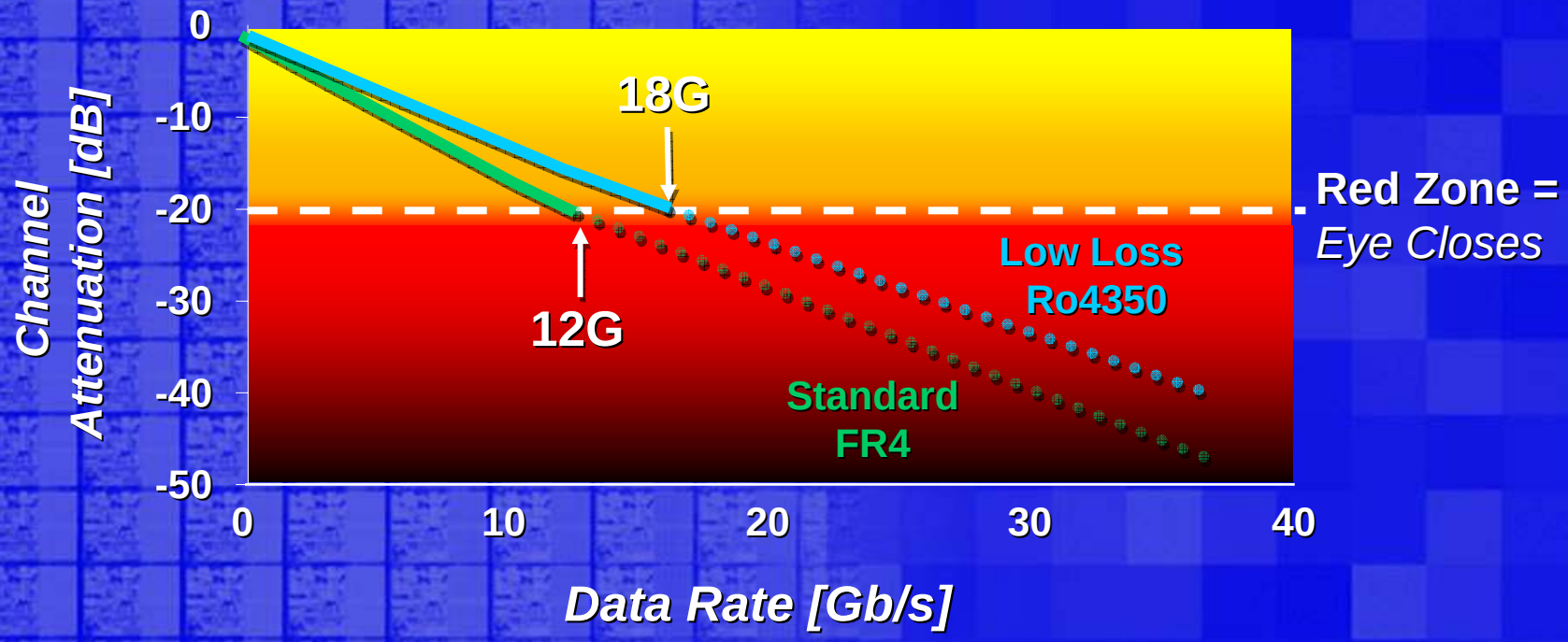
Copper Approaching Limits

Simulation of 20” channel transmitter w/ equalization



Copper scaling more challenging. Headroom getting squeezed.

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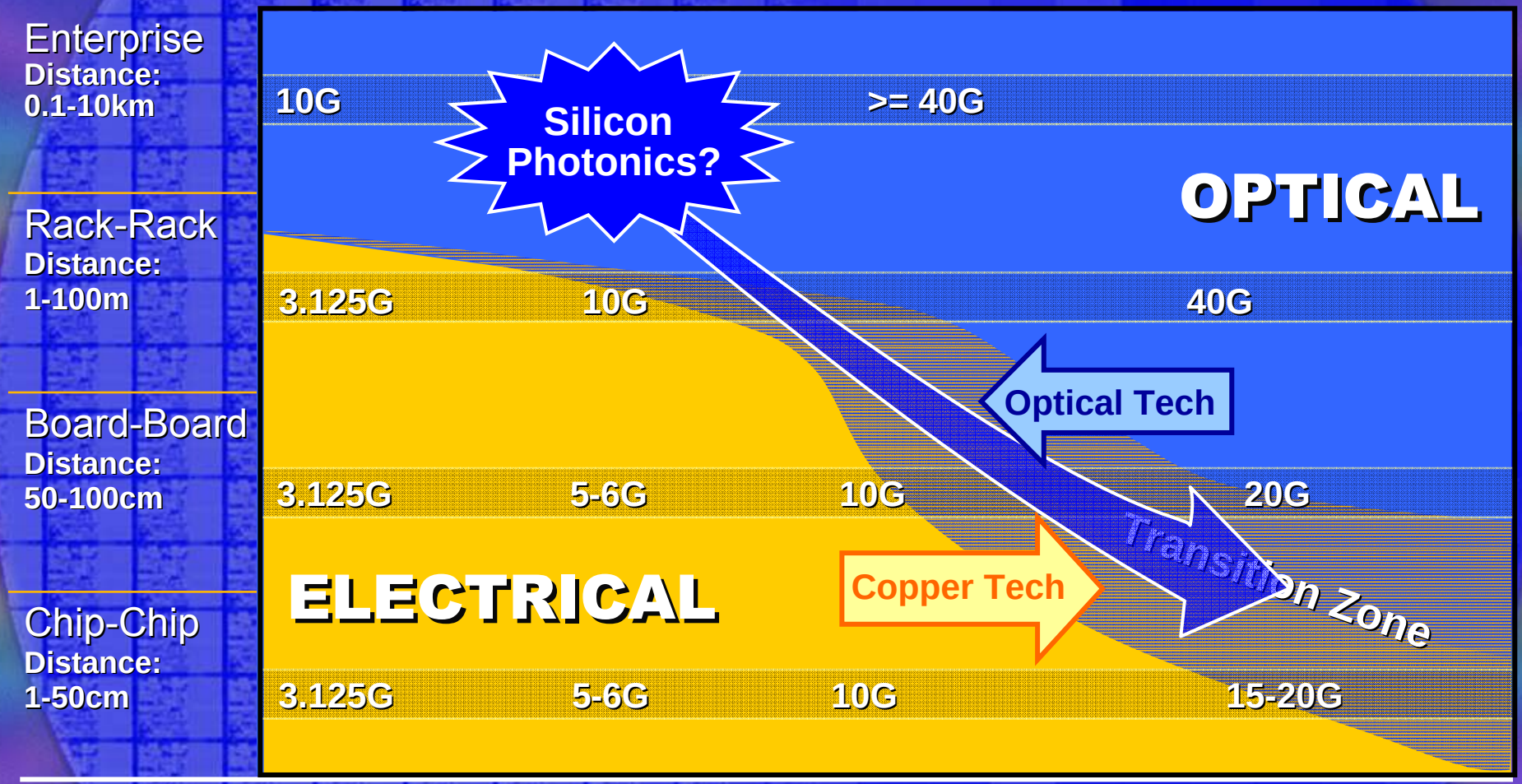
Electrical to Optical



Transition driven by cost

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The Opportunity of Silicon Photonics

- Take advantage of enormous ($ billions) CMOS infrastructure, process learning, and capacity
  - Available tools: litho requirements typically >90nm
  - Draft continued investment going forward
- Potential to integrate multiple optical devices
- Micromachining could provide smart packaging
- Potential to converge computing & communications

Industry standard silicon manufacturing processes could enable integration, bring volume economics to optical.

To benefit from existing infrastructure optical wafers *must* run alongside product.. i.e CMOS compatible..

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Photonics: *The technology of emission, transmission, control and detection of light (photons) aka fiber-optics & opto-electronics*

Today: *Most photonic devices made with exotic materials, expensive processing, complex packaging*

Silicon Photonics Vision: *Research effort to develop photonic devices using silicon as base material and do this using standard, high volume silicon manufacturing techniques in existing fabs*

Benefit: Bring volume economics to optical communications

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  - amplification and lasing in Silicon Silicon Laser**
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Silicon Pro's and Cons

+ Transparent in 1.3-1.6 µm region
+ CMOS compatibility
+ Low cost
+ High-index contrast – small footprint

− No electro-optic effect
− No detection in 1.3-1.6 µm region
− High index contrast – coupling
− Lacks efficient light emission

Silicon will not win with passive devices..
Must produce active devices that add functionality

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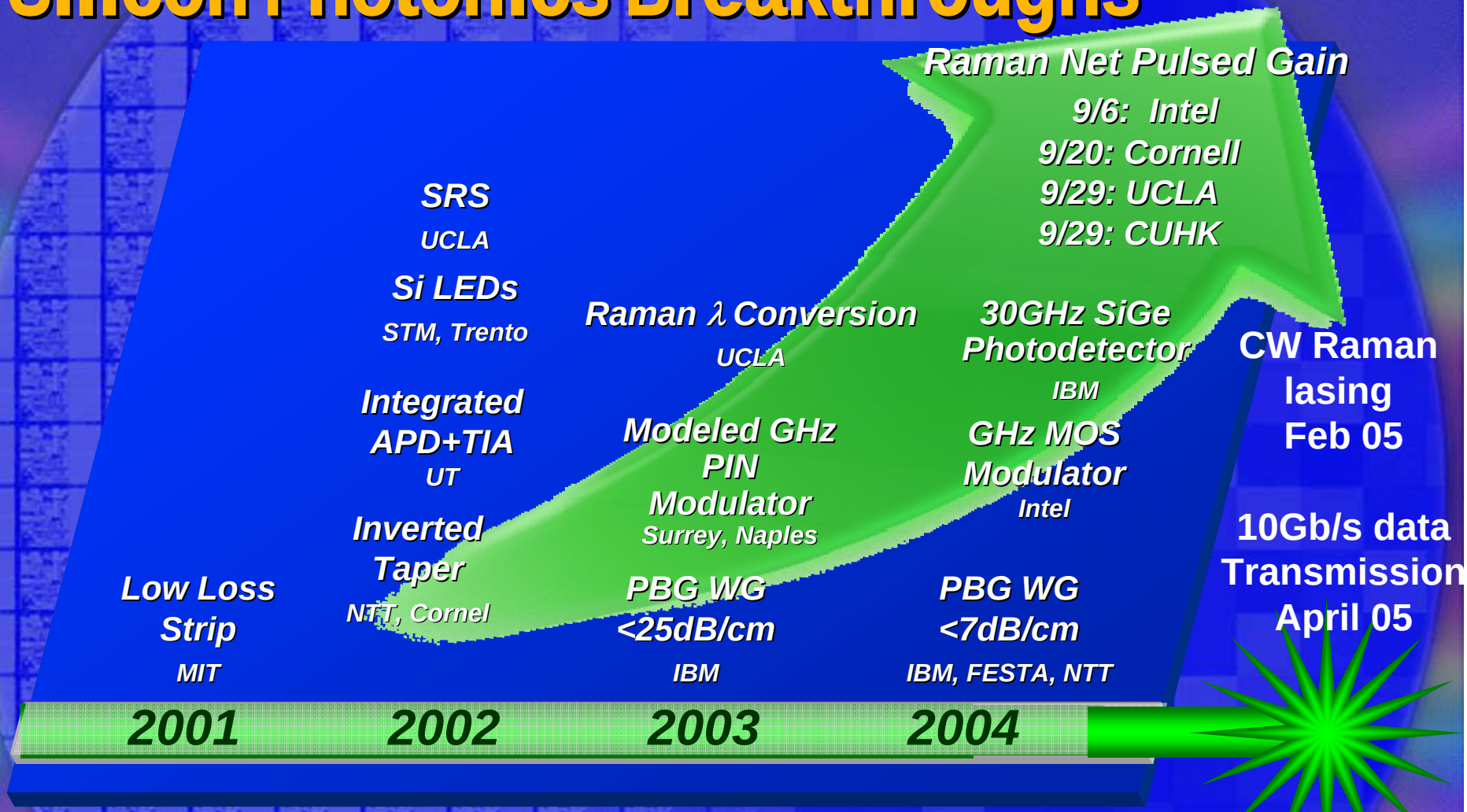
Silicon Photonics Breakthroughs



Research progress In Recent Years Is Accelerating

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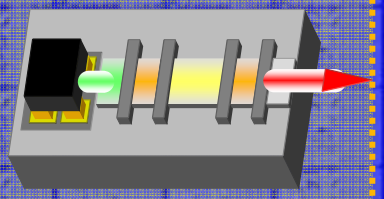
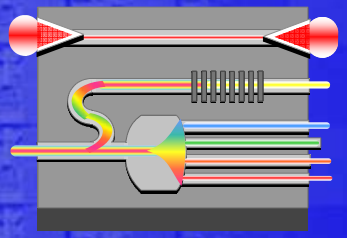
Intel's Silicon Photonics Research

1. Develop photonic building blocks in silicon

1) Light Source

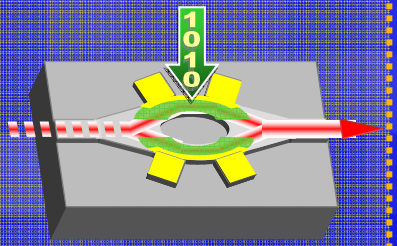


2) Guide Light



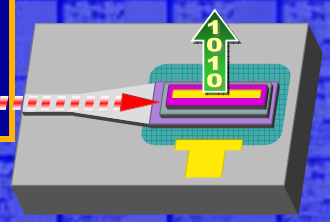
Waveguides devices

3) Modulation



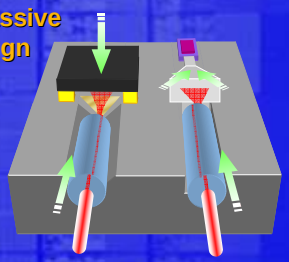
First Continuous Silicon Laser
(Nature 2/17/05)

4) Photo-detection

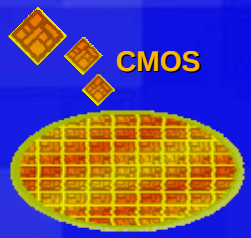


SiGe Photodetectors

5) Low Cost Assembly



6) Intelligence



1GHz
(Nature Feb '04)
10 Gb/s
(April 05)

First Prove that silicon is viable material for photonics

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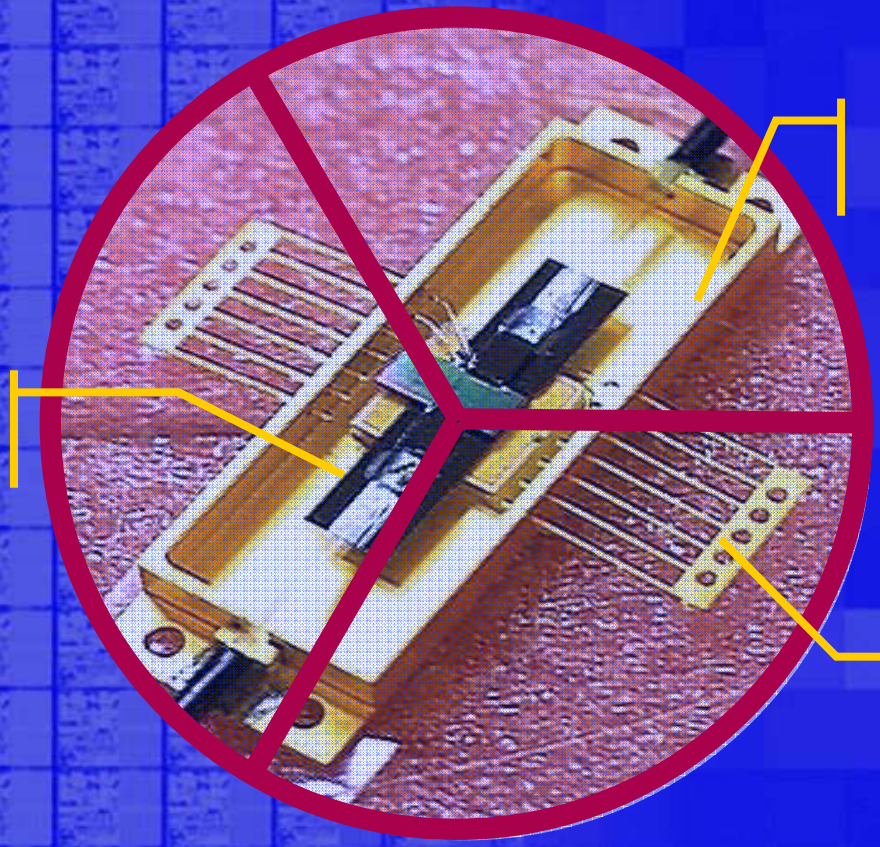
Packaging

Approximate Optical Product Cost Breakdown



In addition to device costs, packaging and testing costs must drop with to enable high volume photonics

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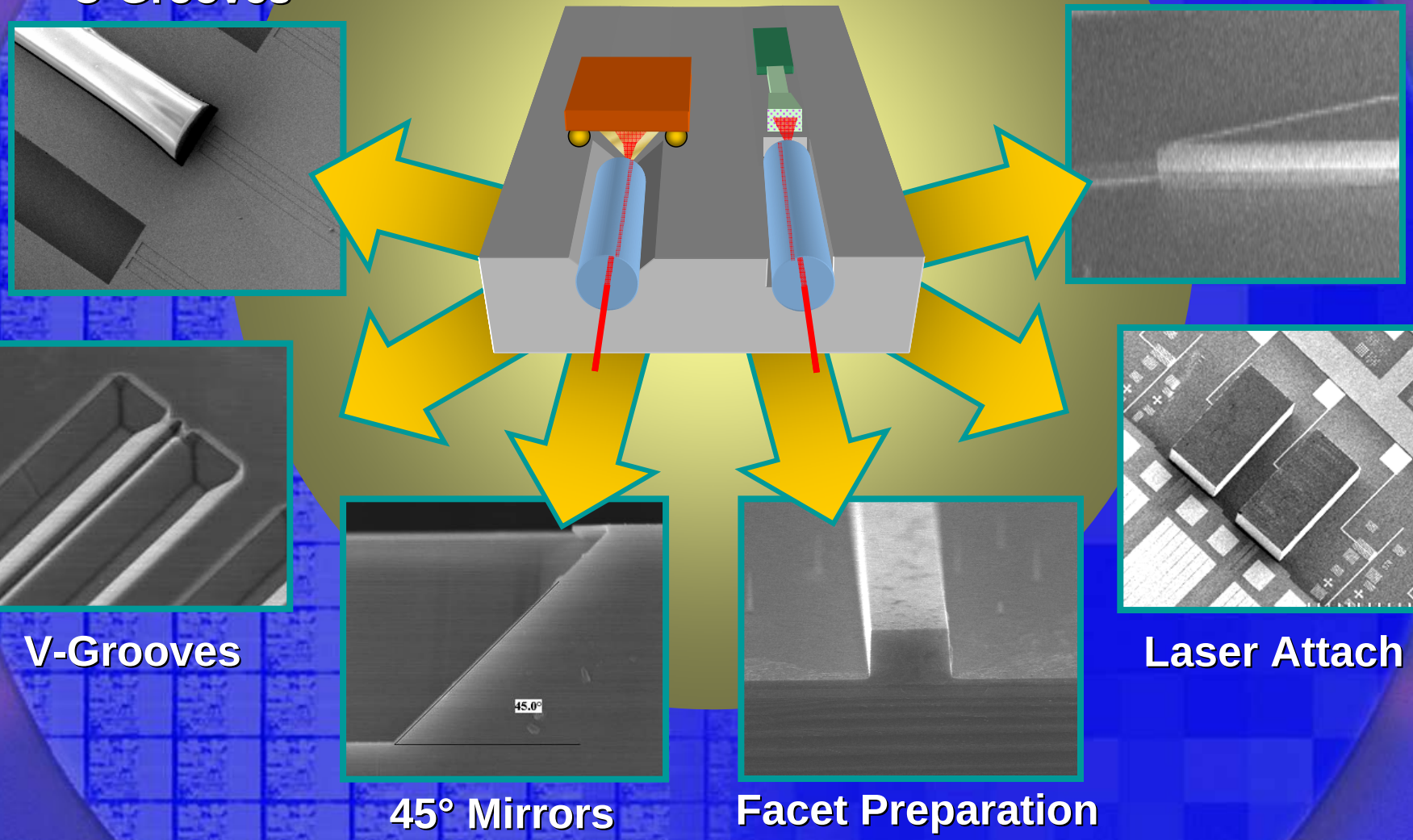
Micromachining for Packaging

Use standard pick and place technologies
along with litho defined silicon micromaching



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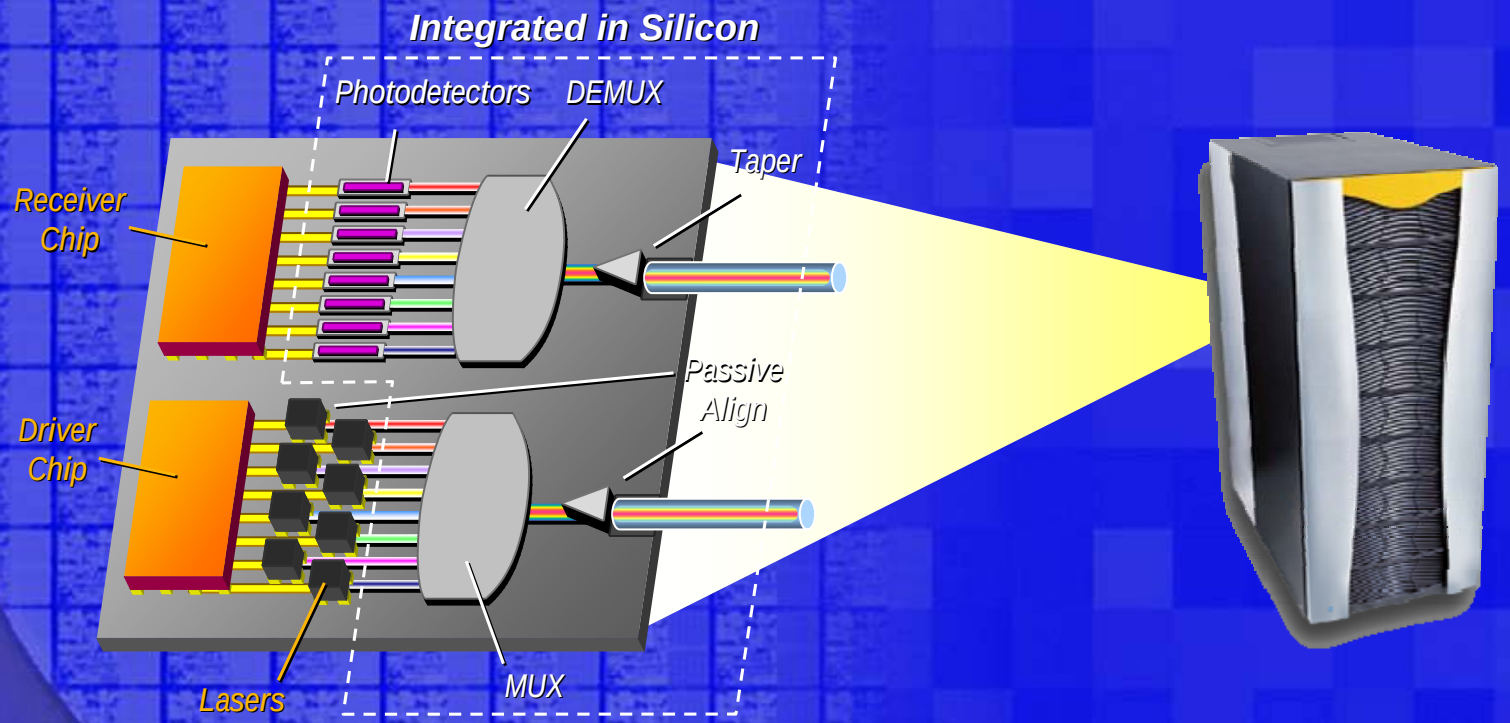
Intel's Silicon Photonics Research

1. Develop photonic building blocks in silicon
2. Integrate increasing functionality directly onto silicon



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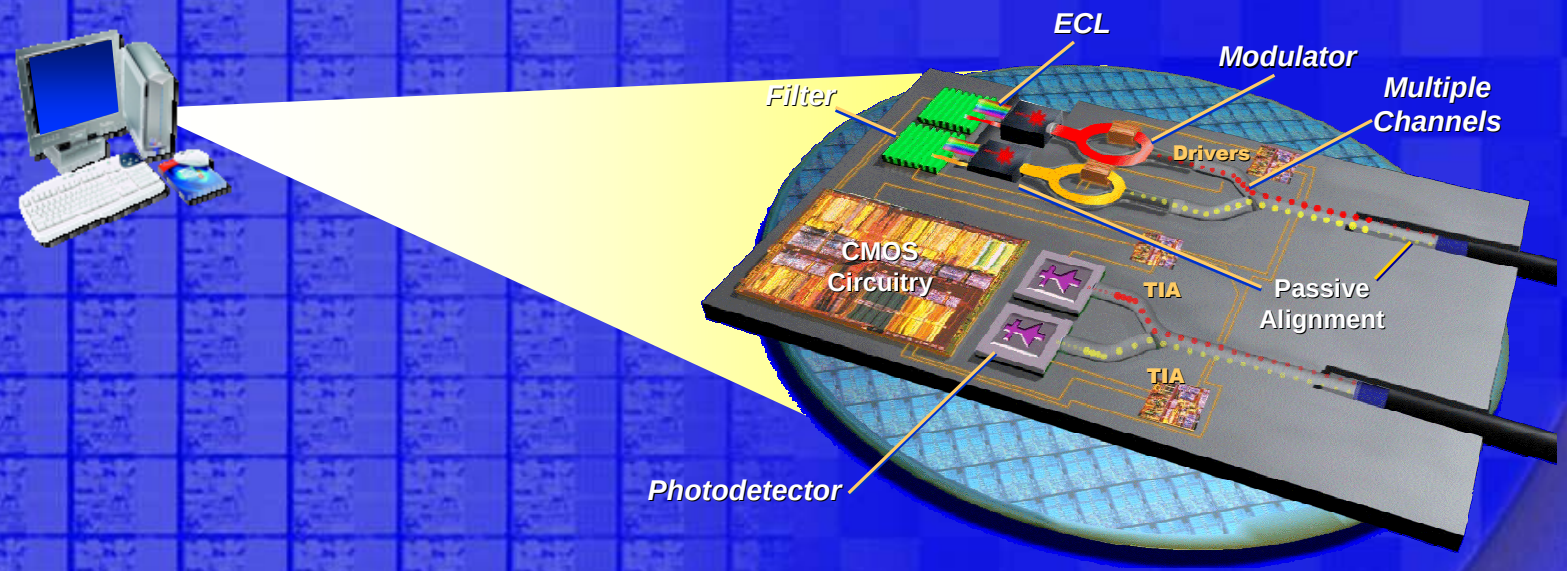
Intel's Silicon Photonics Research

1. Develop photonic building blocks in silicon
2. Integrate increasing functionality directly onto silicon
3. Long term explore monolithic integration



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SILICON LASER
What We announced on Feb 17th

- Research Breakthrough:1st Continuous Silicon Laser
  - Silicon laser cavity on a single chip
  - Published in the journal *Nature* on February 17, 2005

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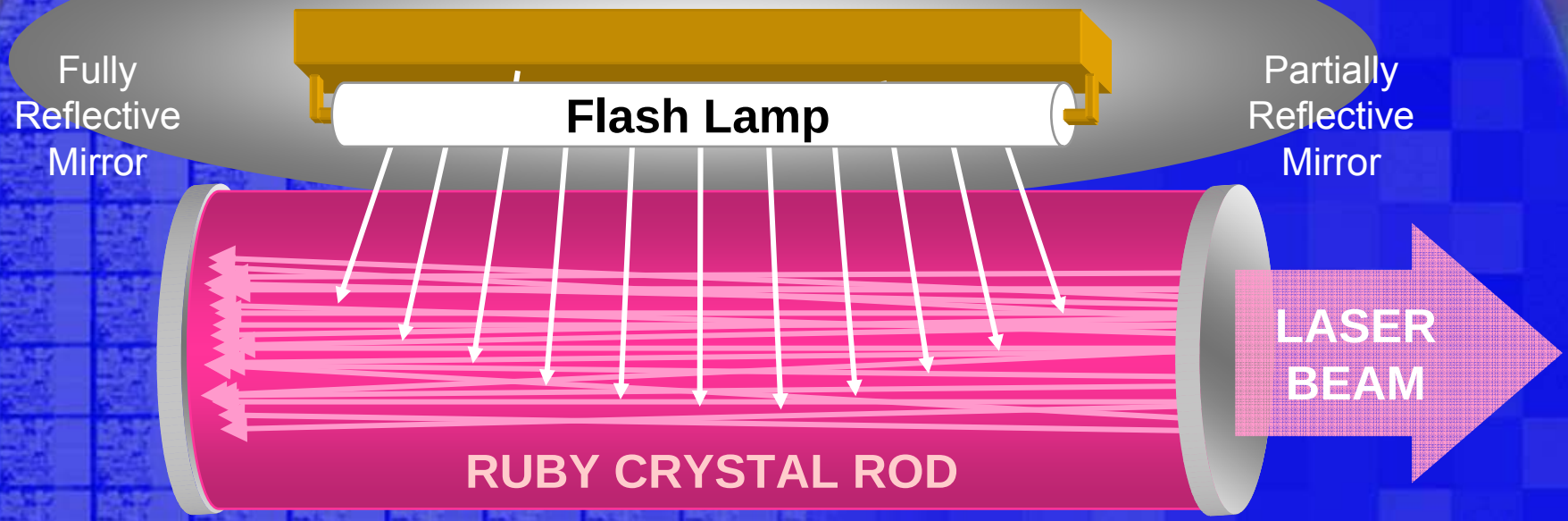
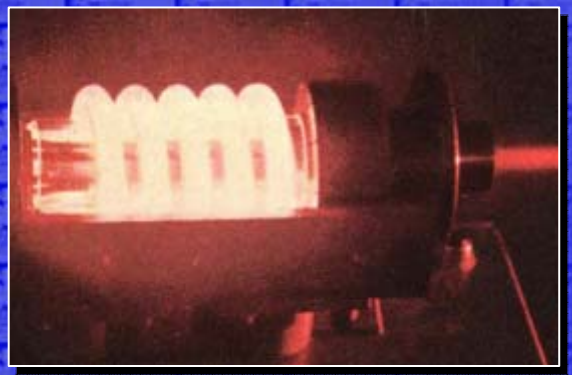
The First Laser

Developed by Ted Maiman, published in *Nature*, August 6, 1960.
this ruby laser used a flash lamp as an optical pump





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Raman: (Historical Note)

Raman Effect or Raman Scattering: ***A phenomenon observed in the scattering of light as it passes through a transparent medium; the light undergoes a change in frequency and random alteration in phase due to a change in rotational or vibrational energy of the scattering molecules.***

- Discovered a material effect that is named after him
  - ***Nature*** **published his paper on the effect on March 31, 1928**
  - **He received the Nobel prize in 1930 for his discovery**
- The first laser using the Raman effect was built in 1962
- **Today Raman based amplifiers are used throughout telecom**
  - **Most long distance phone calls will go through a Raman amplifier**

Venkata Raman – Biography

Chandrasekhara Venkata Raman was born at Trichinopoly in Southern India on November 7th, 1888. His father was a lecturer in mathematics and physics so that from the first he was immersed in an academic atmosphere. He entered Presidency College, Madras, in 1902, and in 1904 passed his B.A. examination, winning the first place and the gold medal in physics; in 1907 he gained his M.A. degree, obtaining the highest distinctions.

Typical Raman Amplifier

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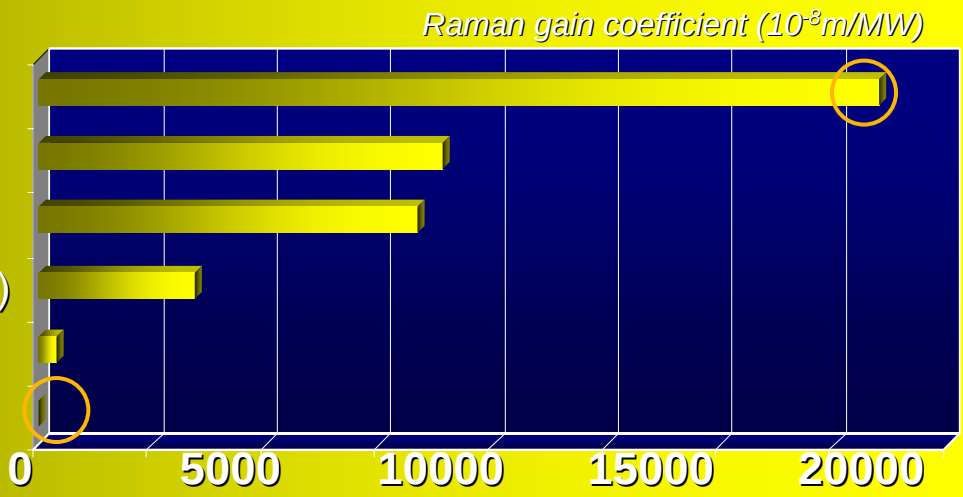
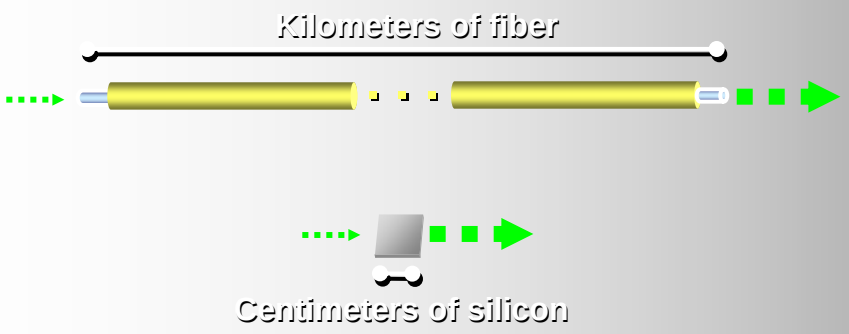
The Raman Effect

Materials

- **Silicon**
- Indium Antimonide (III-V)
- Quartz
- Lithium Niobate (used for modulators)
- Diamond
- Glass Fiber (Raman lasers/amps)





The Raman effect is 10,000 times stronger in silicon than in glass fiber

This allows for significant gain in centimeters instead of kilometers

Fabrication of low-loss silicon waveguides is challenging

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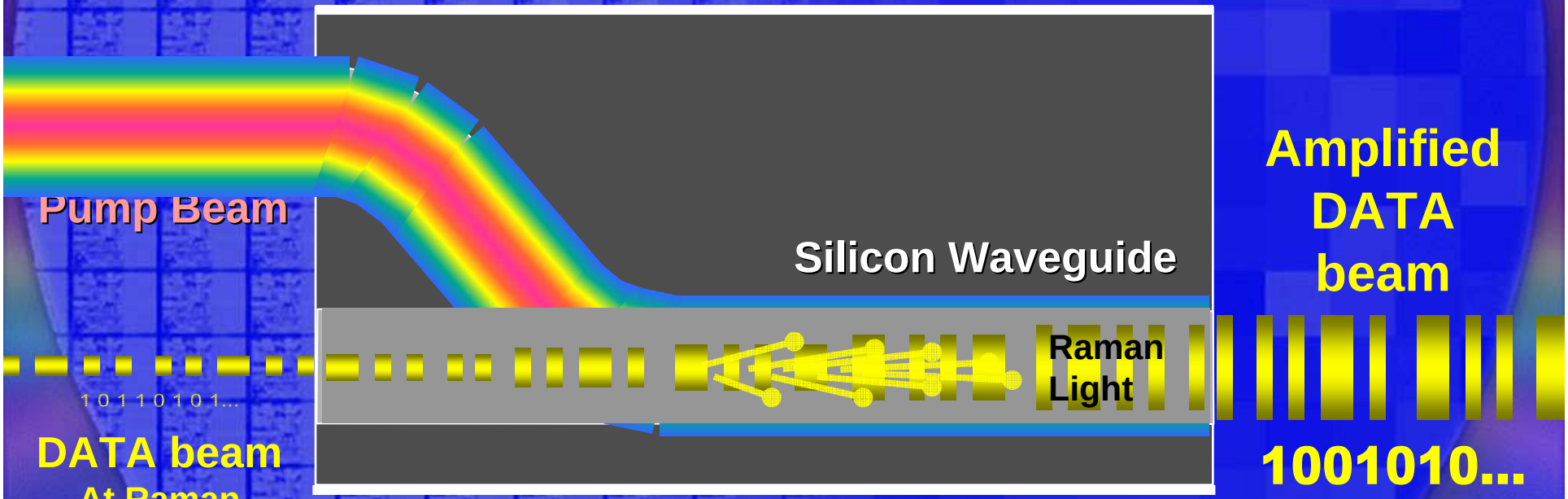
Raman Amplification

Light from a pump beam exchanges energy with vibrating silicon atoms, causing energy to be transferred to the Raman wavelength.

Passing an optical signal at this wavelength causes amplification.



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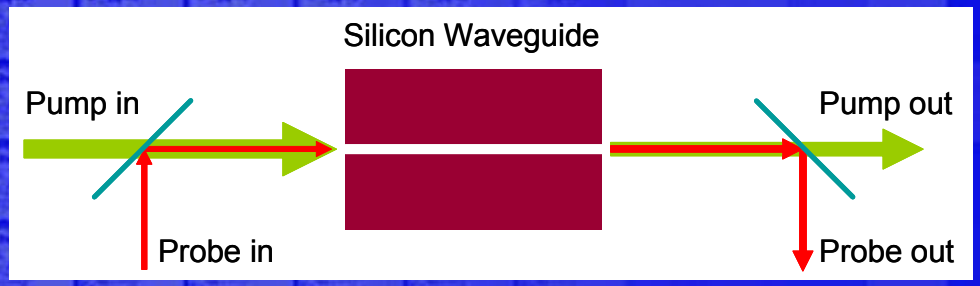
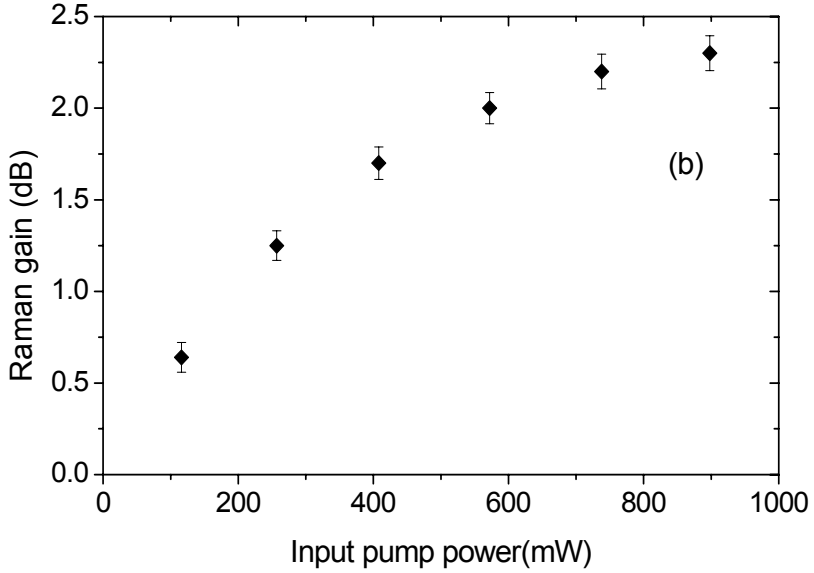
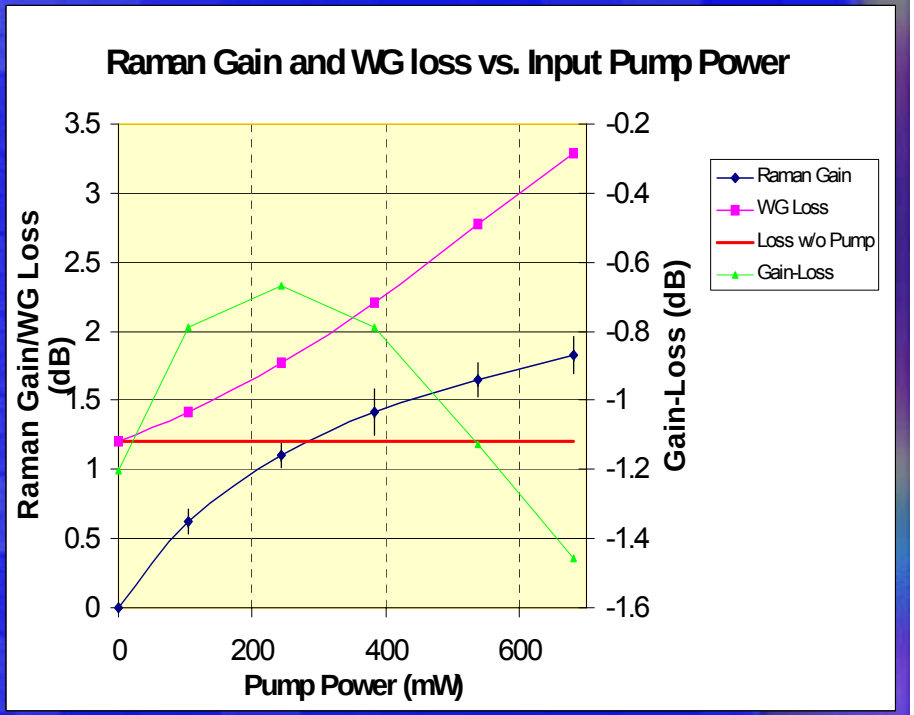
Raman Gain in Silicon



Pump/probe experiment





CW Gain Saturation due to TPA induced FCA

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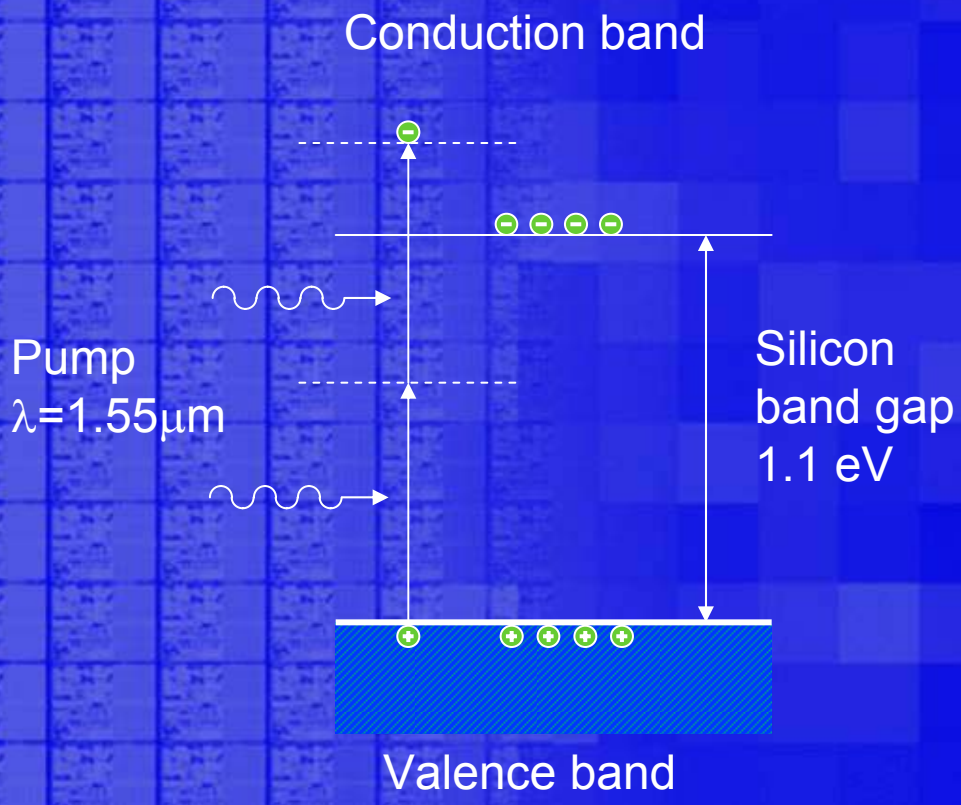
Two Photon Absorption in Silicon



Two photons can simultaneously hit an atom
Combined energy enough to kick free an electron

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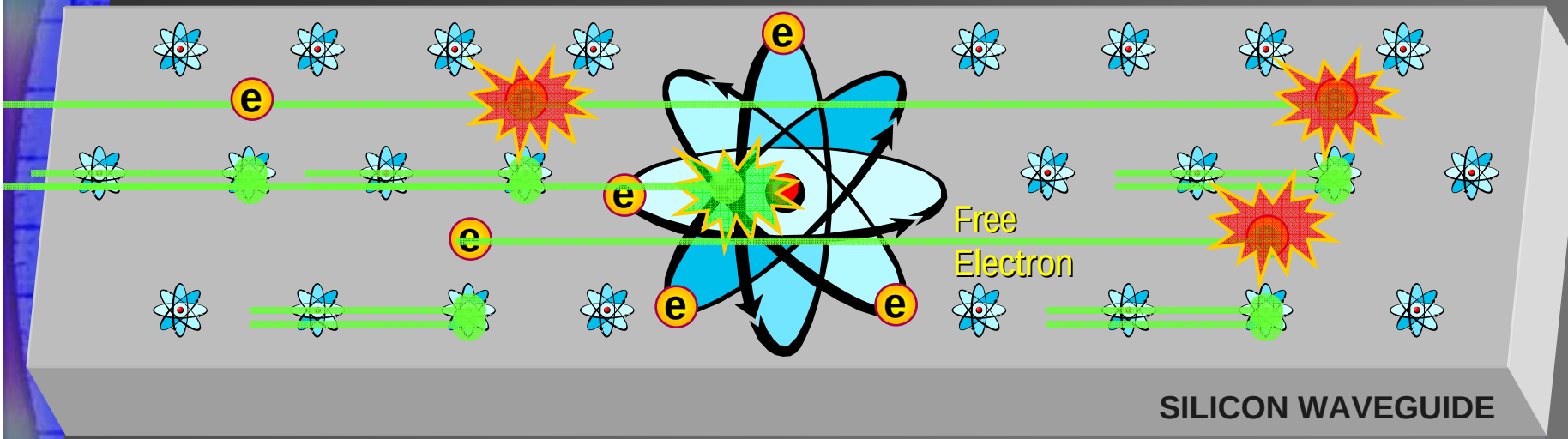
Two Photon Absorption

In silicon, one infrared photon doesn't have the energy to free an electron



But, occasionally, *two* photons can knock an electron out of orbit.

Free electrons *absorb individual photons and cancel Raman gain*

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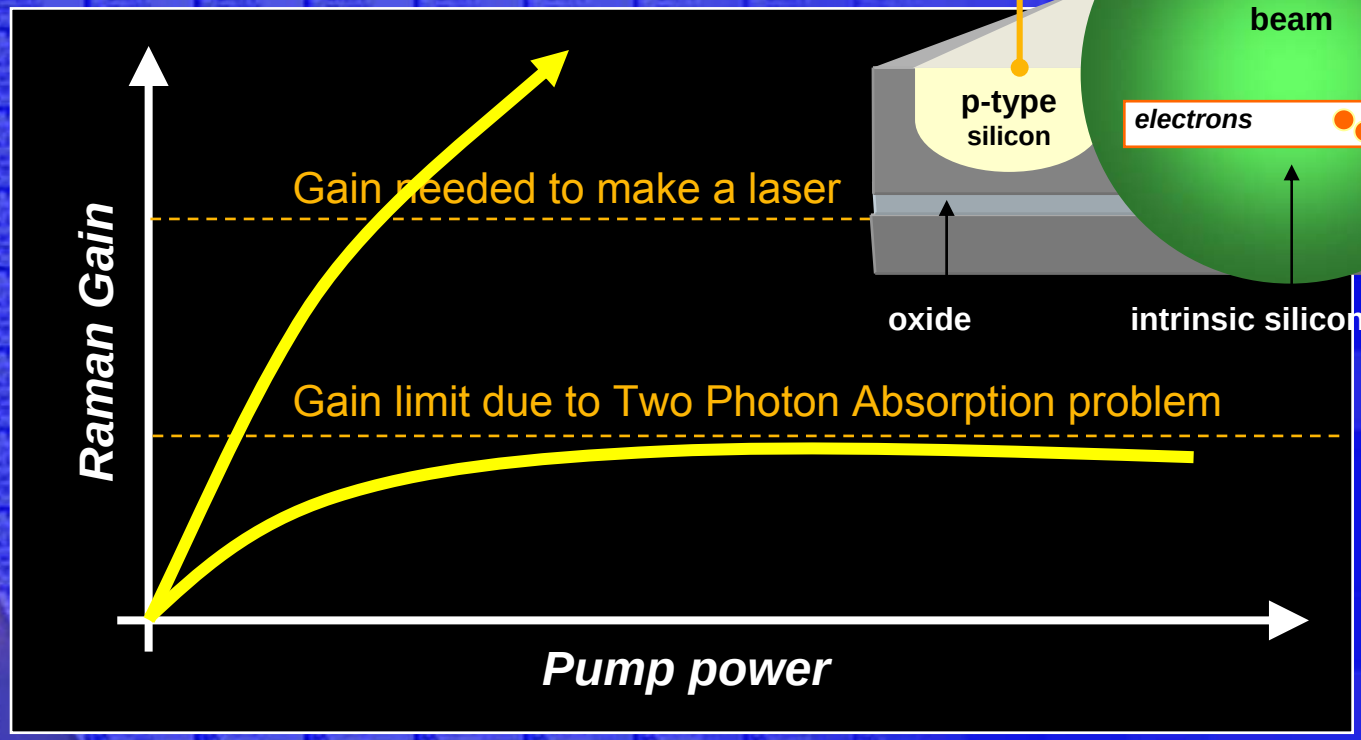
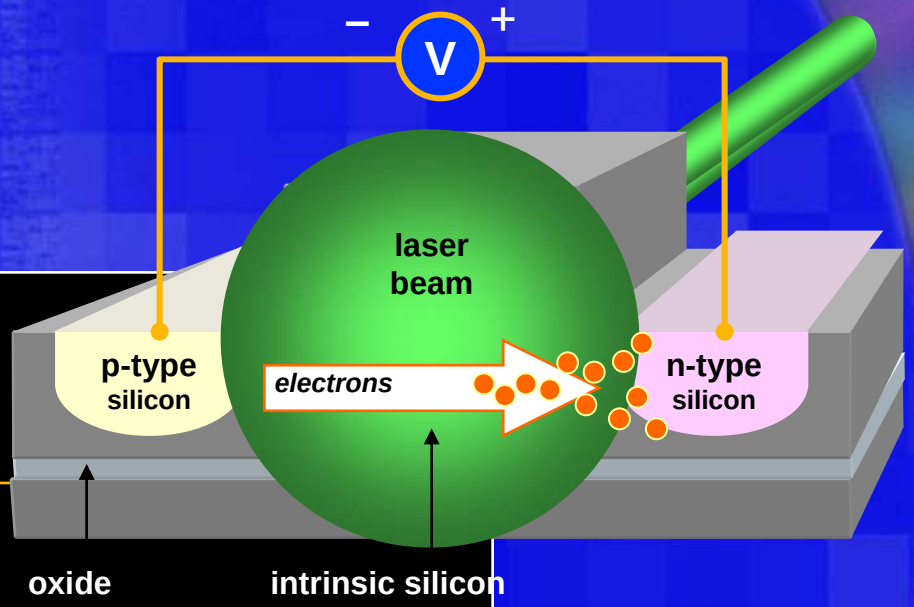
Overcoming TPA induced FCA





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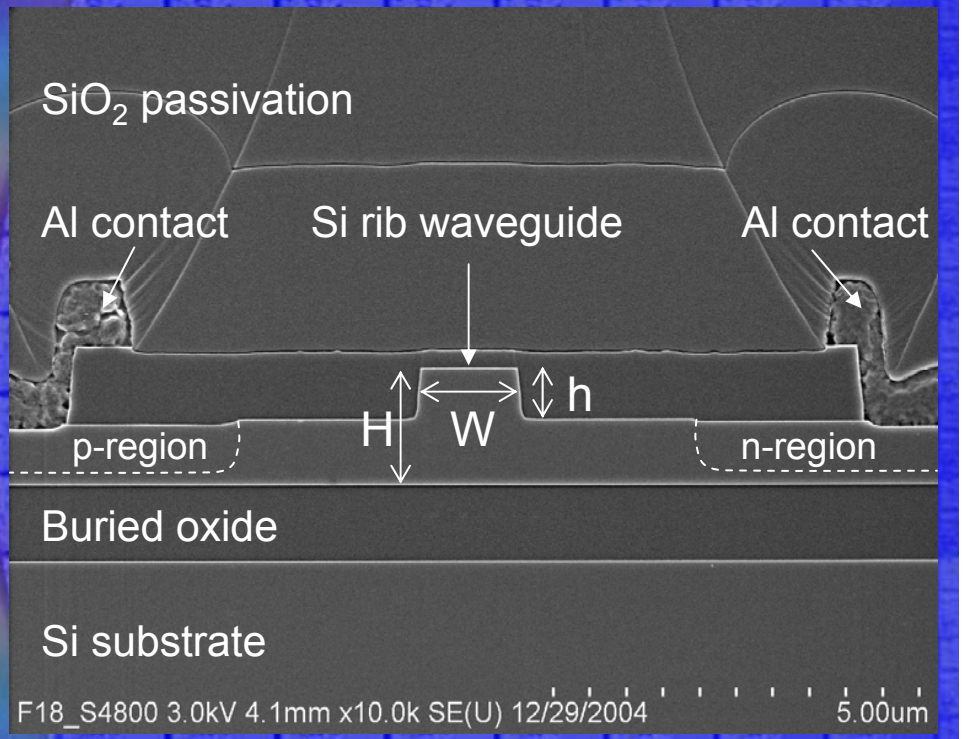
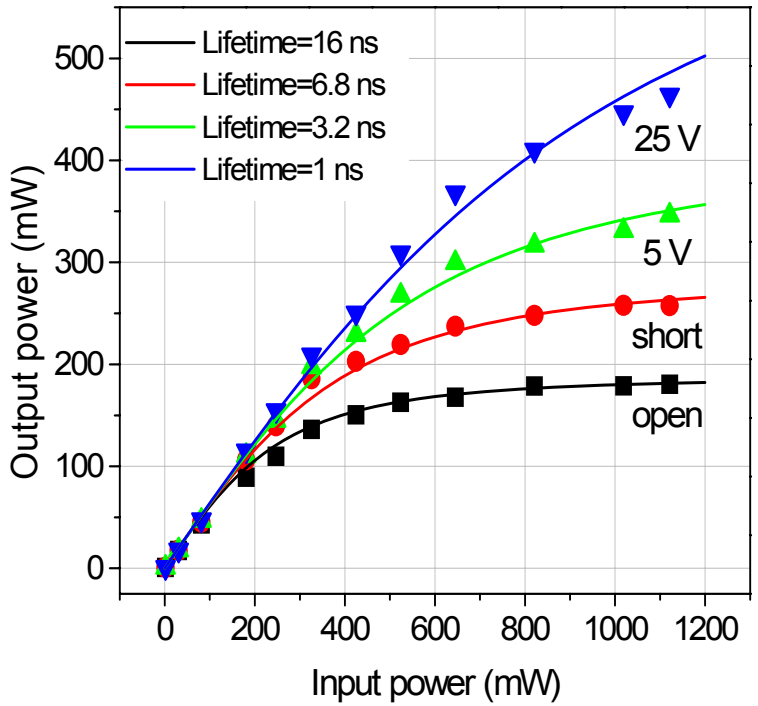
Effective Carrier lifetime reduction



PIN Cross-section



TPA coeff ~ 0.5 cm/GW, α 0.39 dB/cm,
FCA cross sect 1.45e-17 cm^2 @ 1550 nm.
The lifetime is used as a fitting parameter

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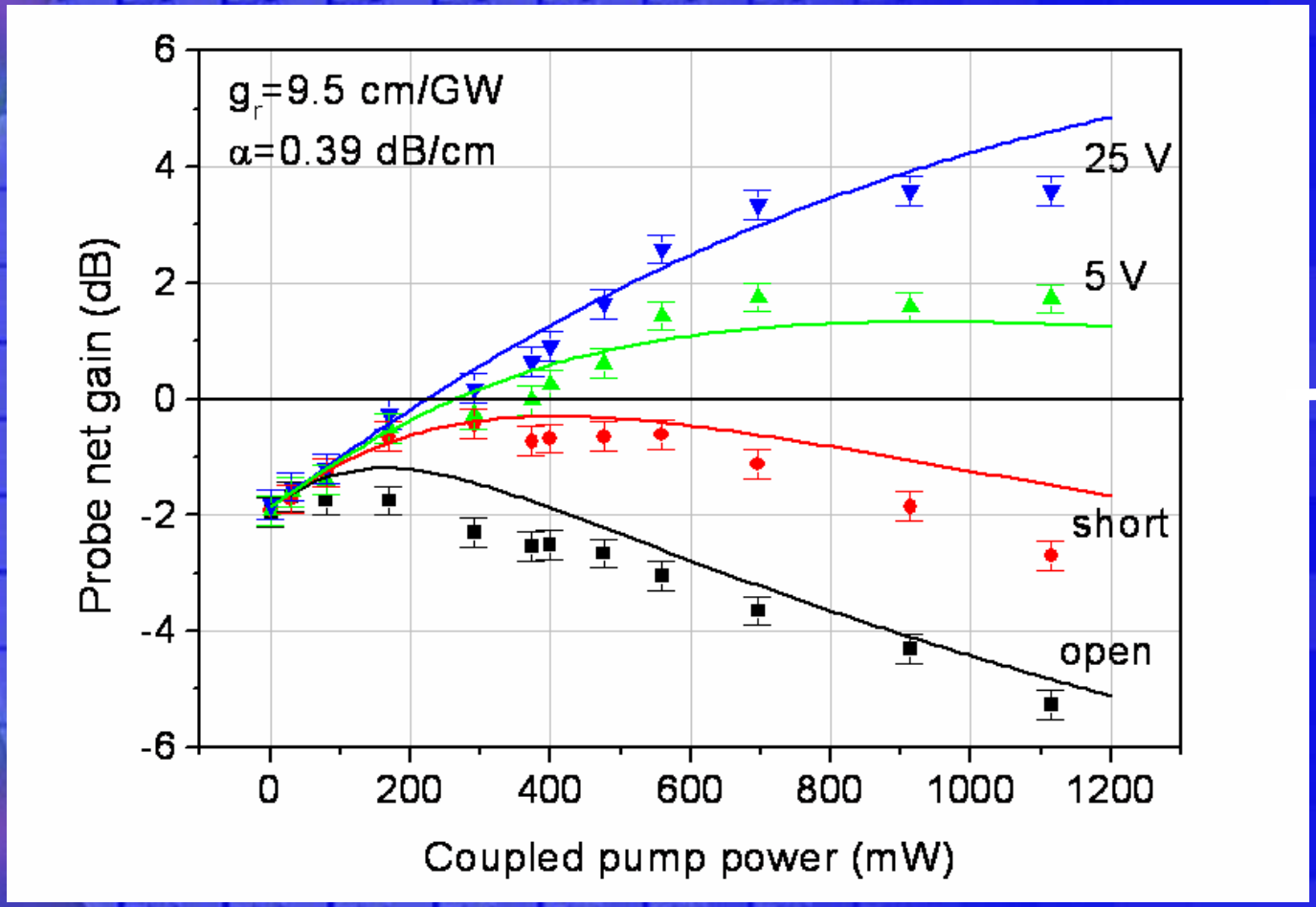
CW gain vs. reverse bias voltage

R. Jones et al. Optics Express 13 (519-525) 2005



NET GAIN

NO NET GAIN

Pump λ=1550 nm Signal λ=1686 nm

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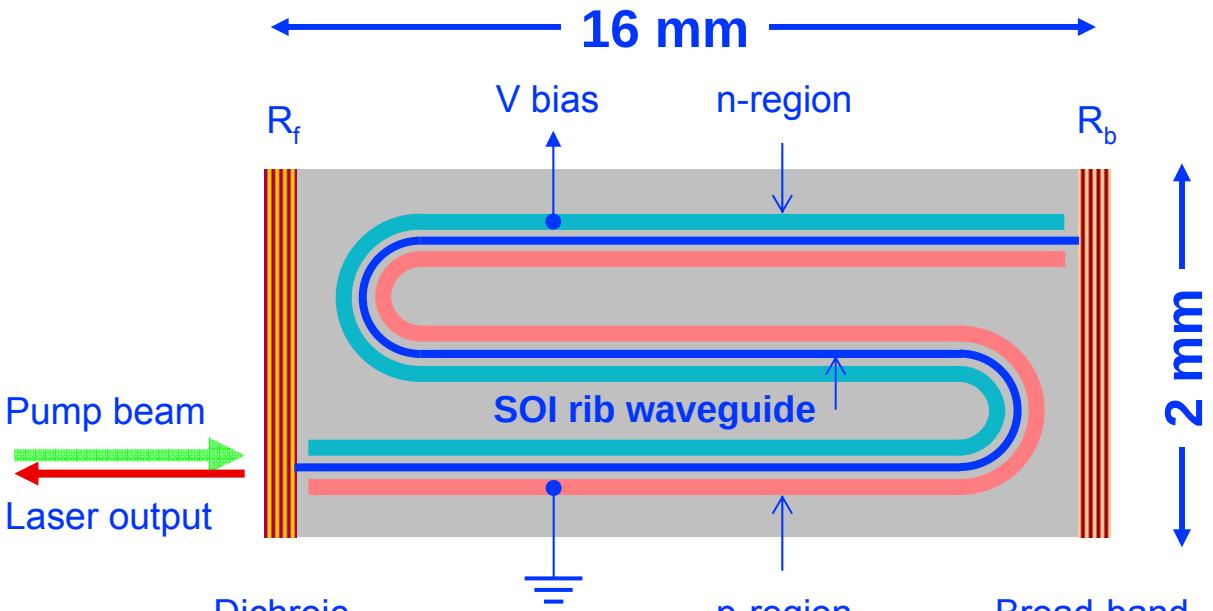
With gain can build Laser:
Silicon Waveguide Cavity



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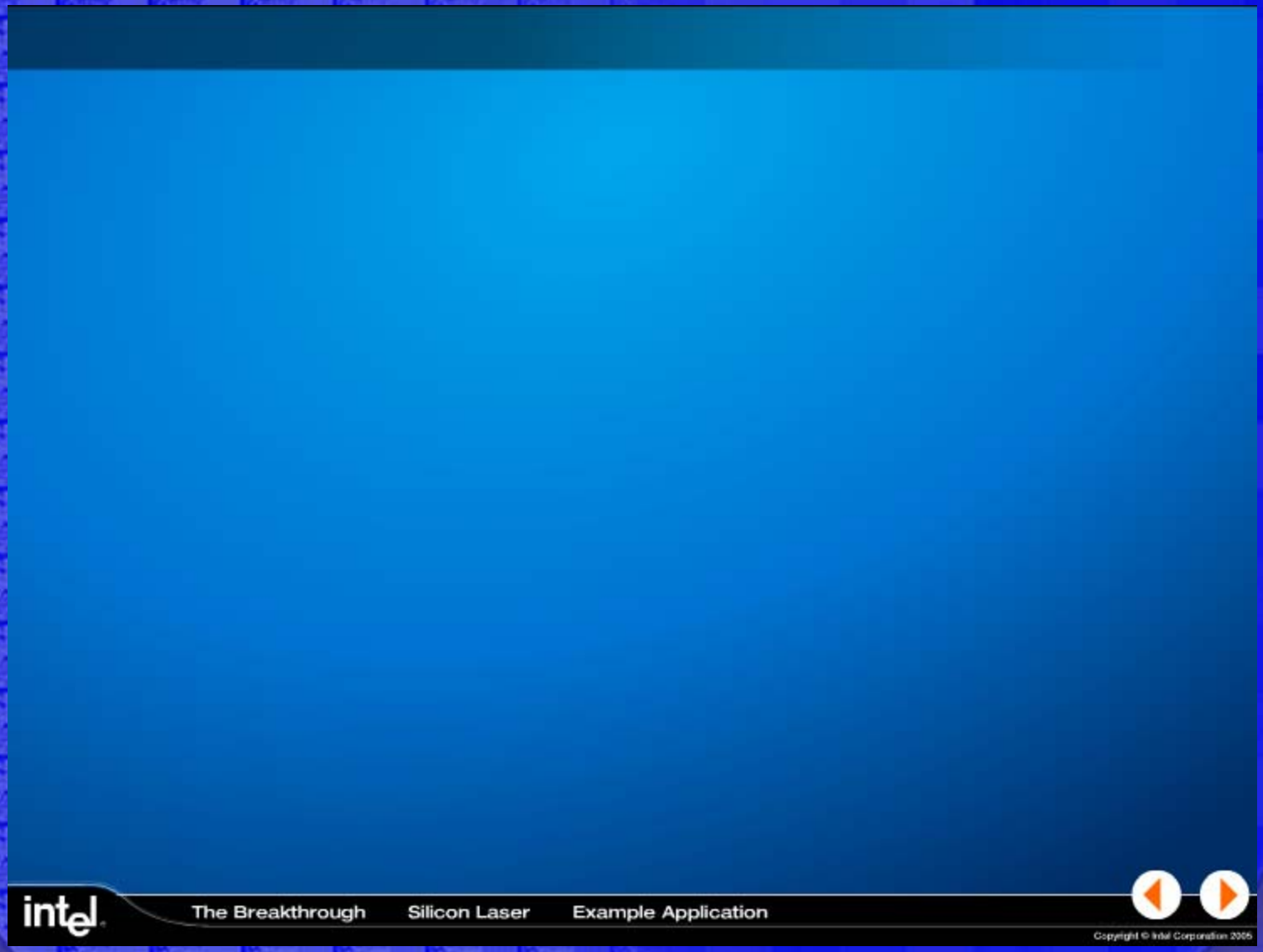
Animation

Click in box while in slide show mode to start



Click outside animation box after animation

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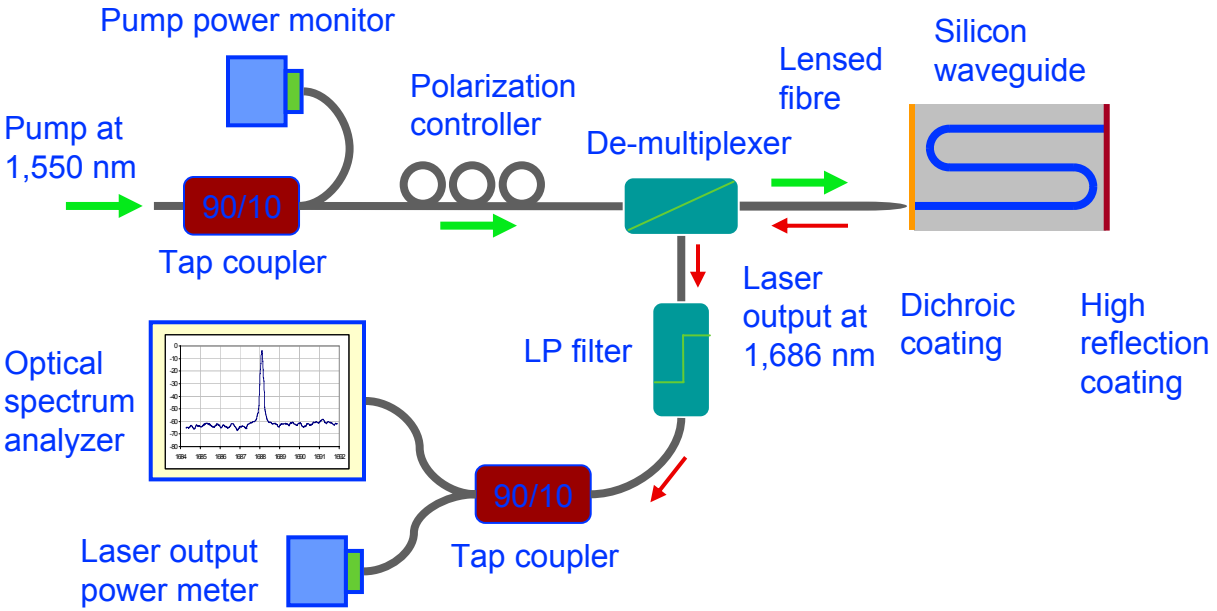
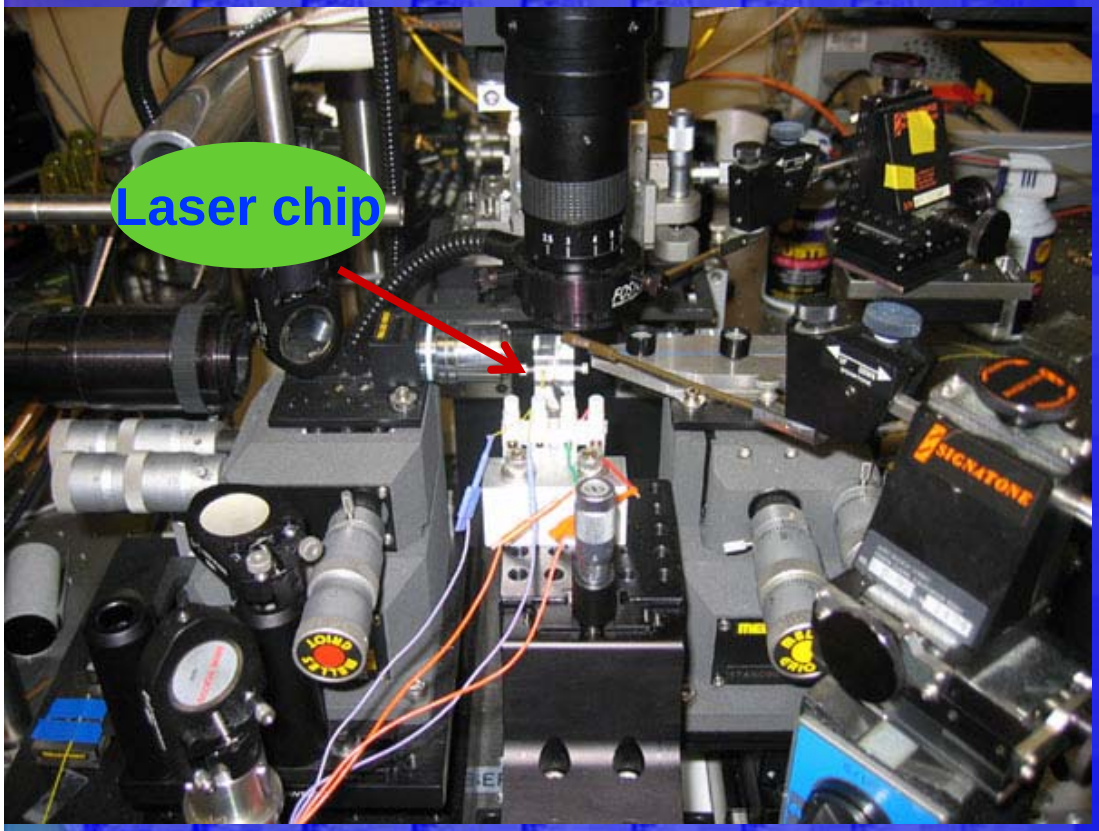
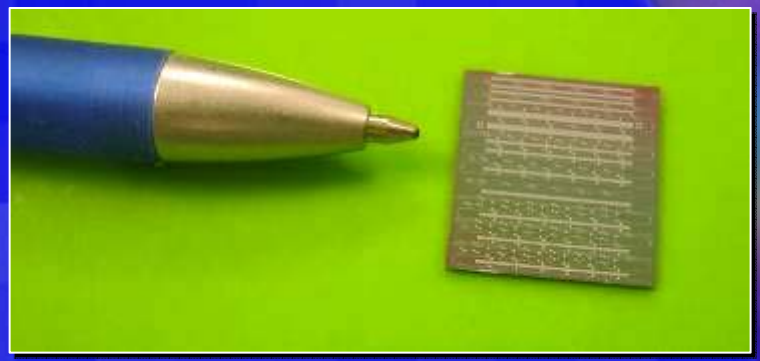
Experimental setup

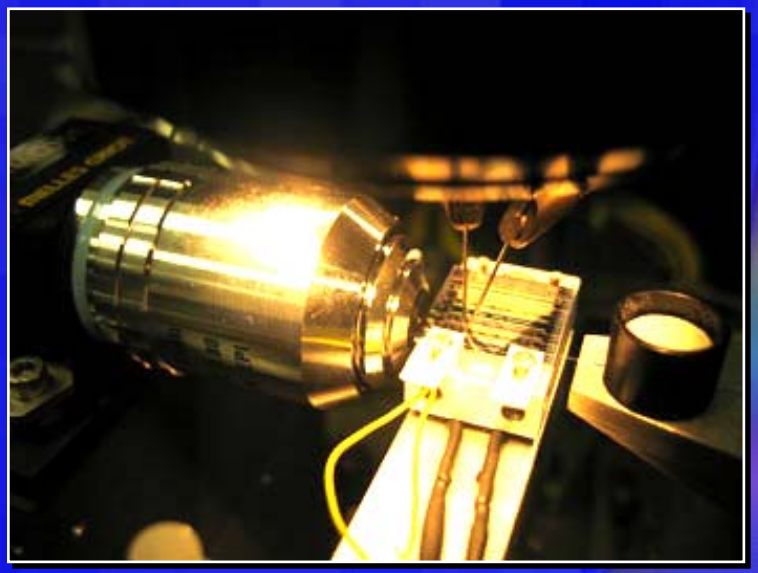


Experimental Set up



Test chip with 8 laser WG's





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Typical Lasing Criteria

- Threshold behavior:
  - rapid growth in output power when gain > loss
- Spectral linewidth narrowing:
  - Coherent light emission

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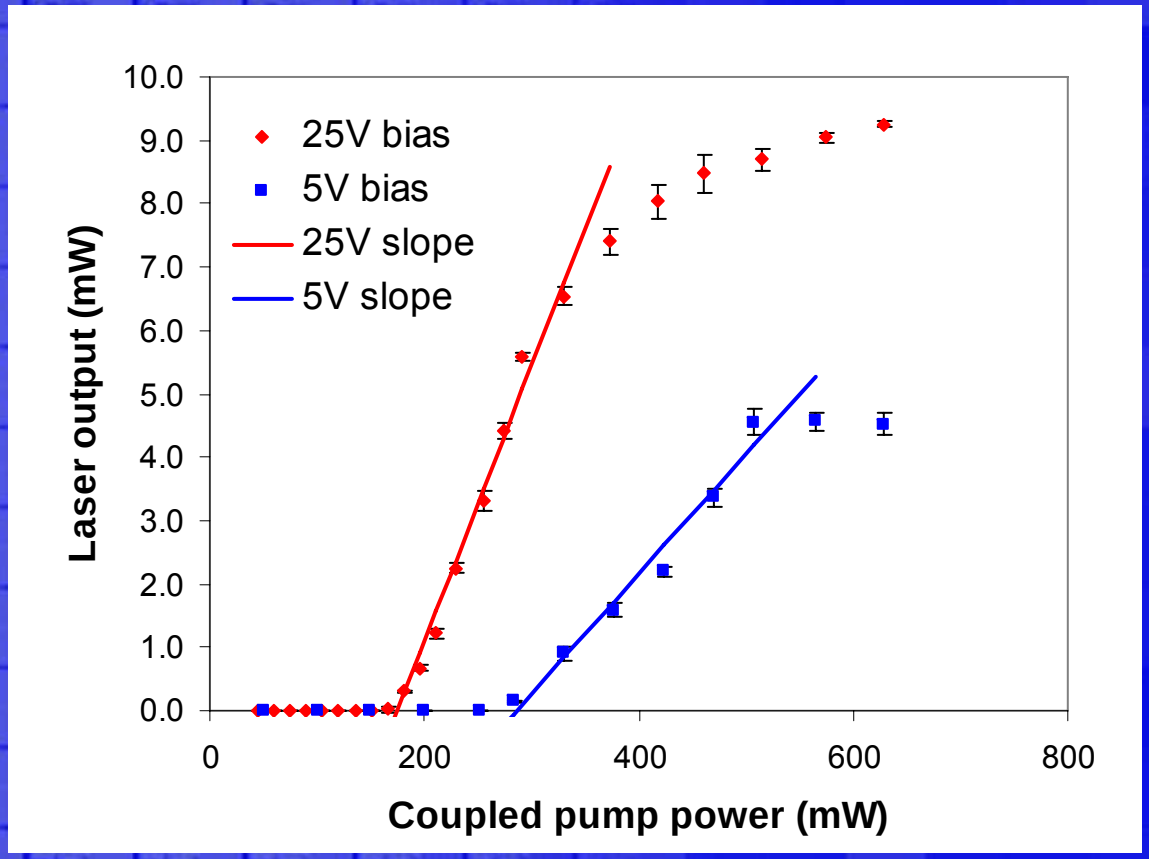
Threshold, Efficiency, and PIN effect



Laser turns on at threshold, when gain per pass in cavity becomes greater than the loss.

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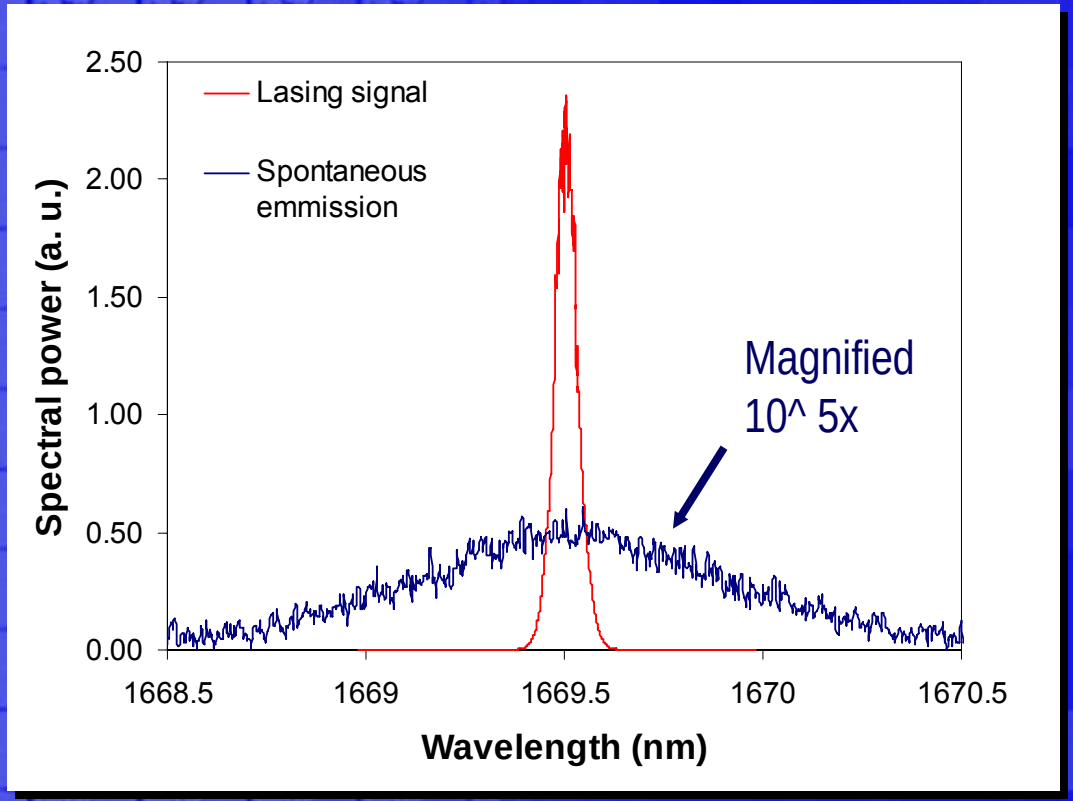
Spontaneous emission vs. laser spectrum



When lasing, the spectrum becomes much more narrow and much higher in power.

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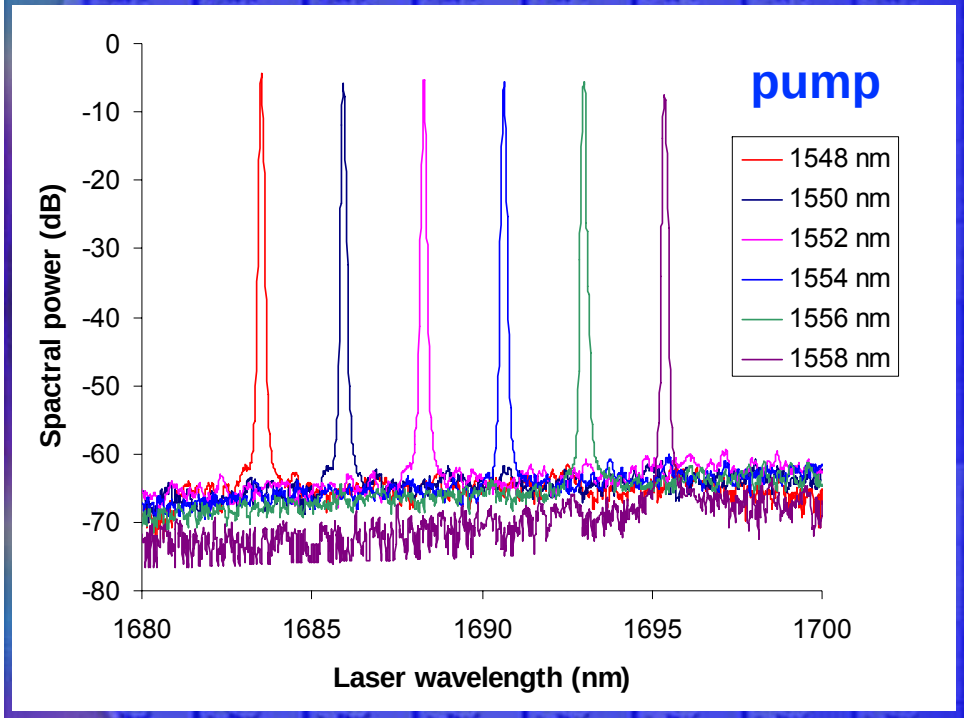
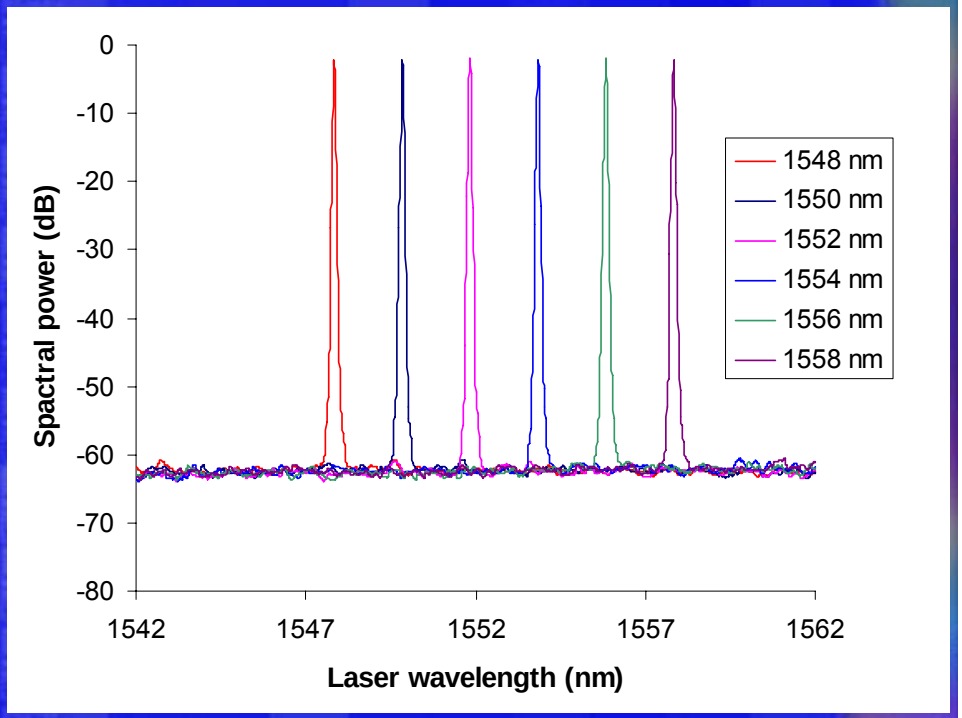
Wavelength tuning (comparison)





Silicon Raman laser

Commercial ECDL

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Potential Applications

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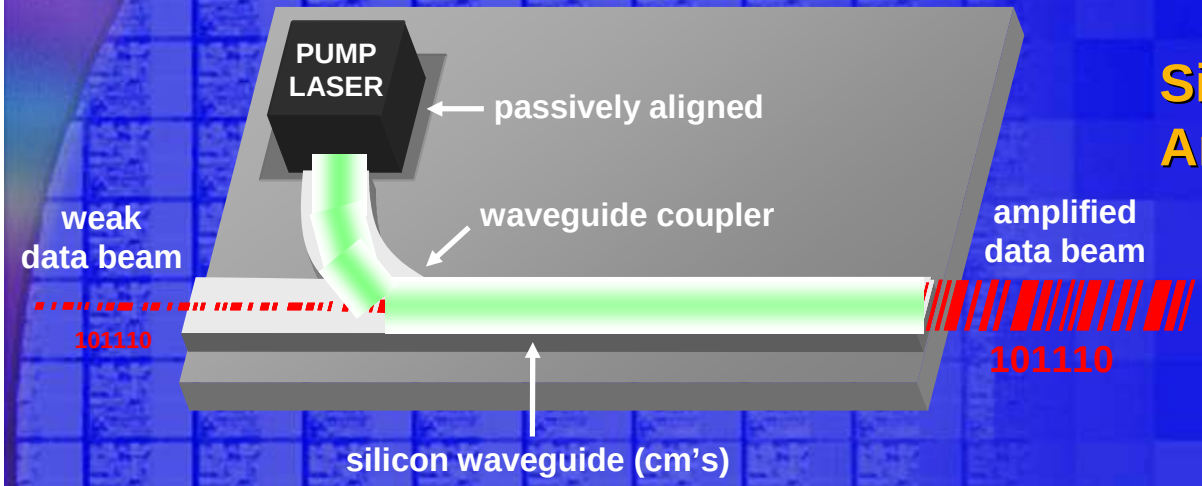
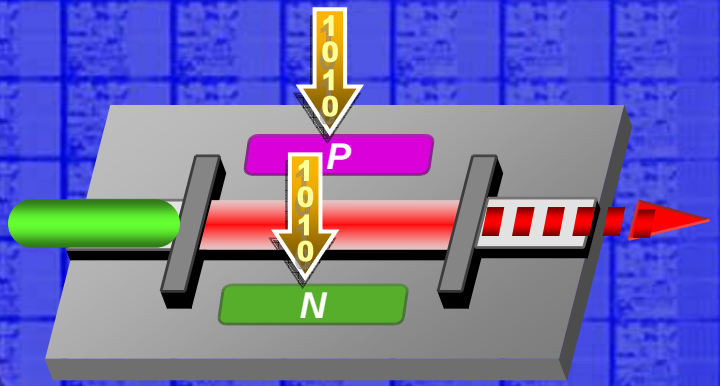
Communications Applications

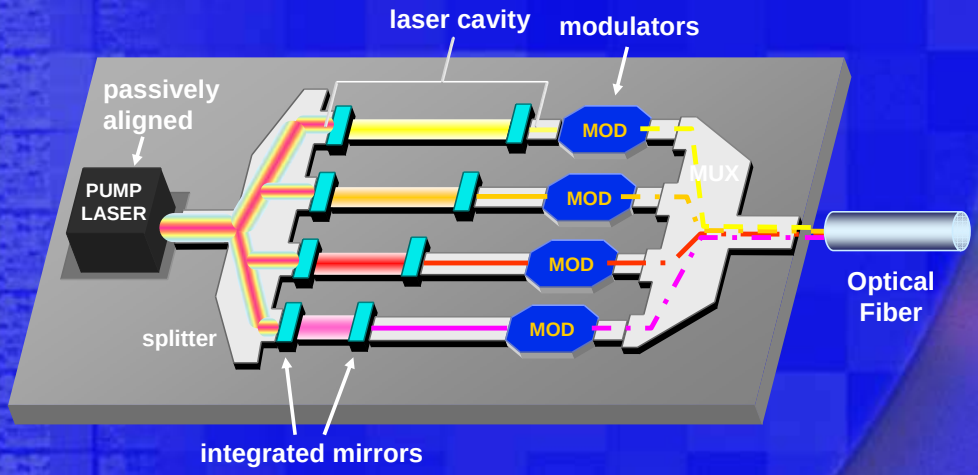


Si Raman Amplifier



Si Raman Modulator

Si Multi-Channel Transmitter



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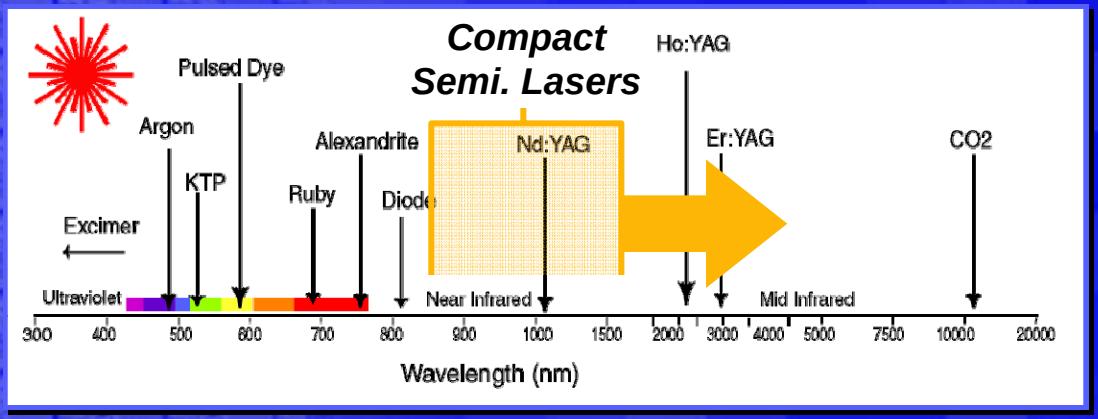
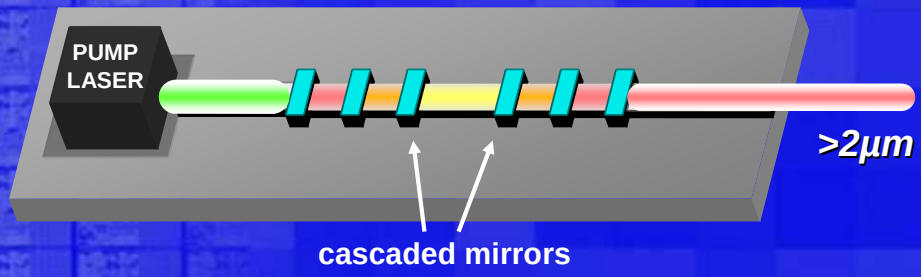
Covering the Gaps

2.1µm Ho:YAG laser

2.9µm Er:YAG laser

- Different wavelengths require different types of lasers
- Mid-Infrared very difficult for compact semiconductors
- Raman Lasers could enable lasers at these wavelengths
- Applications in sensing, analysis, medicine, and others





Could enable lasers for a variety of applications

*Third p

intel

Summary

- Long term convergence opportunities are with silicon
- B/W will continue drive conversion of optical into interconnects
- Tremendous progress from research community
  - Need to continue pushing & improving performance
- Integration is next set of challenges
  - Will be challenging but will bring new functionality and form factors
- In order to benefit Technologies must be CMOS compatible to benefit from HVM & infrastructure

Silicon will not win with individual devices, but with integrated modules that bring increased total functionality & intelligence at a lower cost

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Backup..

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