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WOCC 2005

WIRELESS & OPTICAL COMMUNICATIONS CONFERENCE

Perspectives on Photonic Integration

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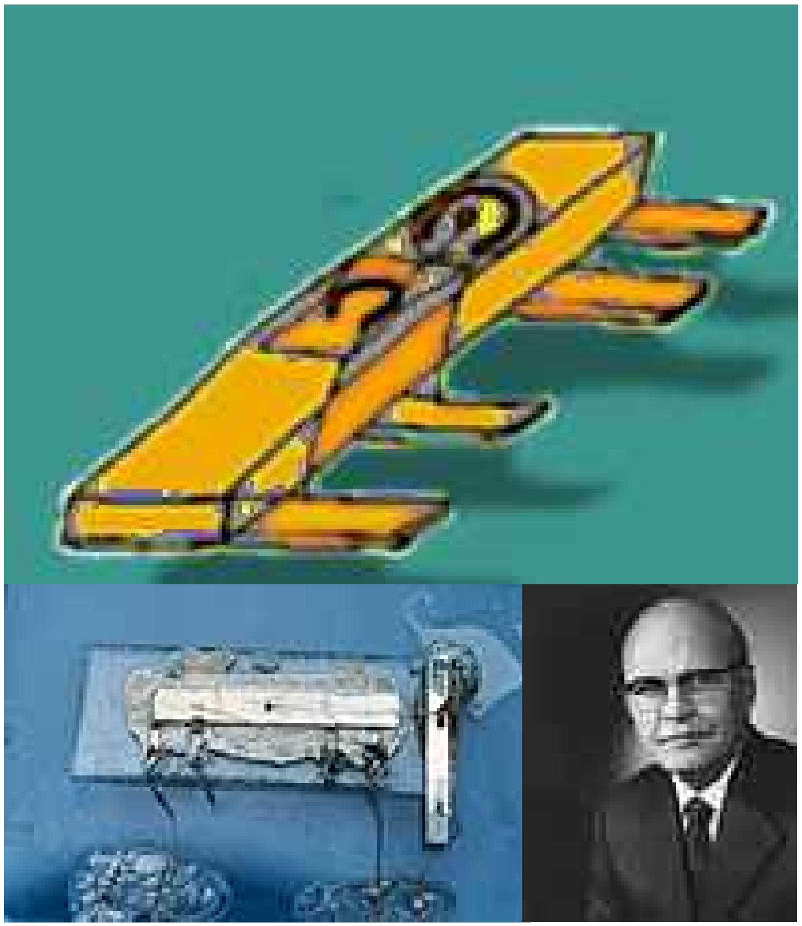
OUTLINE:

- **Photonic Integration:**
  - what it isn't
  - what it is
- **Status, market-induced trends, challenges**

The greatest story of Integration …

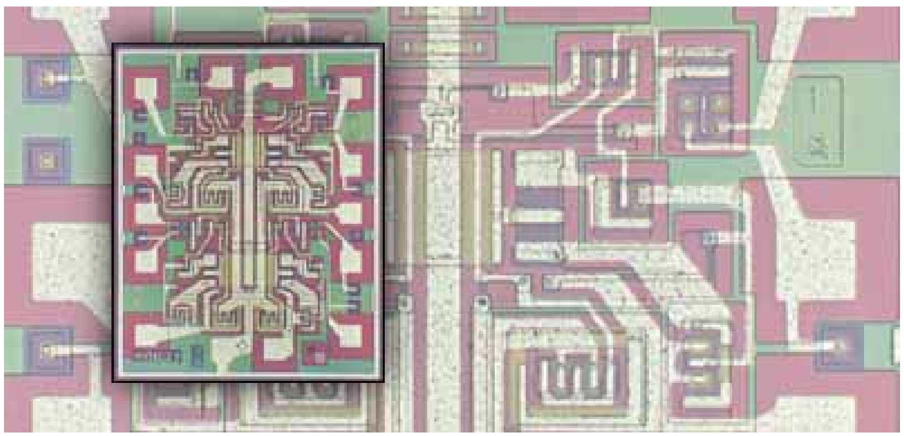


- Sketch from Jack Kilby’s lab notebook of IC concept at TI
- Use semiconductor for circuit elements
  - p-n junctions for capacitors
  - bulk semi for resistors, etc.
- Demonstrated simple circuits like flip-flop, oscillators, etc., in Ge

Silicon Planar Processing …

- Noyce at Fairchild simultaneously files IC concept in Si
- Hoerni introduces planar process in Si
- The race is on …

The Digital Revolution Ramps Up!



1966 TTL logic chip

- First commercial IC in 1961
  - 2 logic gates (4 bipolar transistors, 4 resistors)
- Rapid industry advances ensue:
  - Linear ckts, op amps, etc.
  - Digital logic gates

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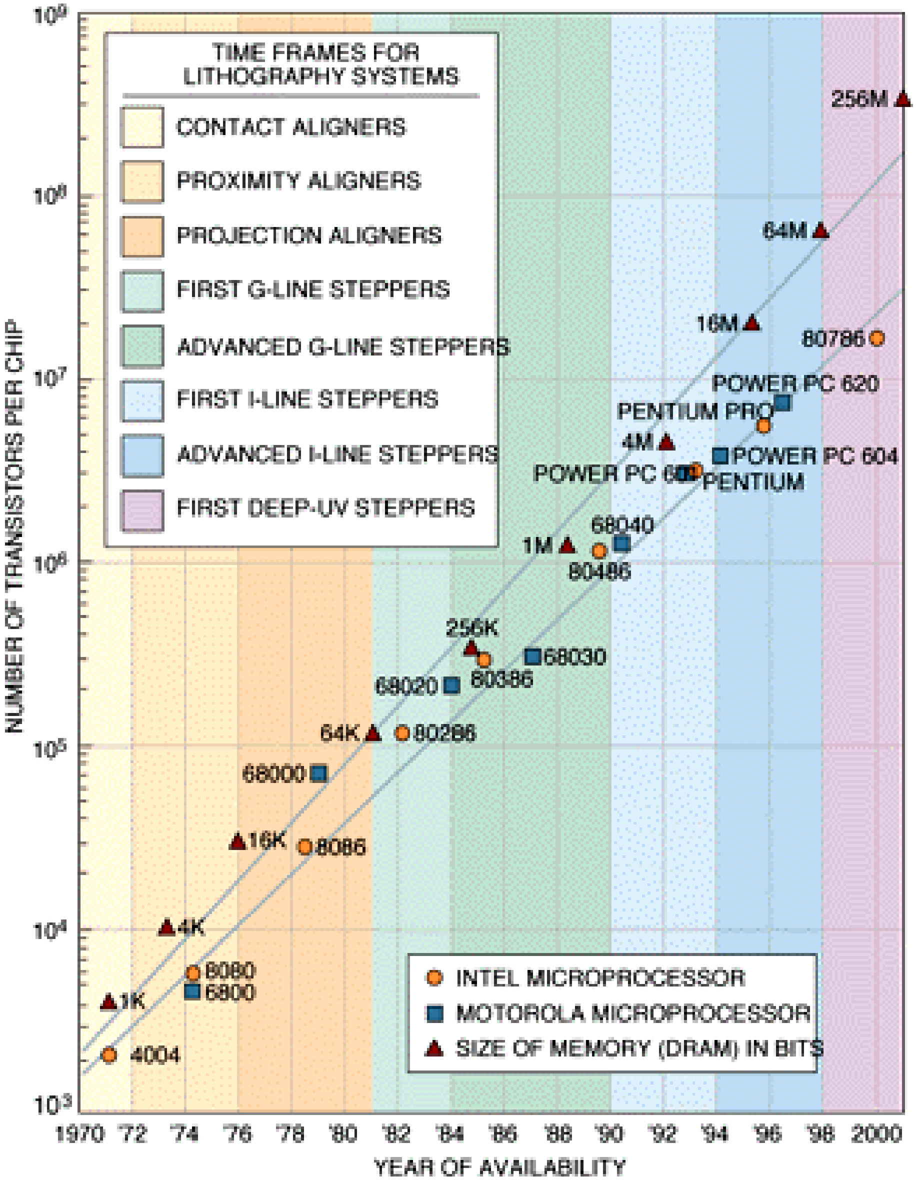
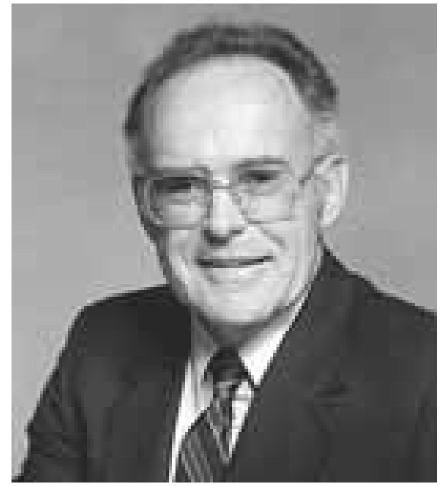
Relentless Advance of IC Integration





- **Moore’s Law (1965)**
- **Doubling in # of transistors every 18 months (60% CAGR)**
- **Example (close to true!):**
  - **1965 most complex digital chip had 64 transistors**
  - **2000 intro of Pentium IV processor w/est. 42 million transistors**
  - **DRAM tracking also**

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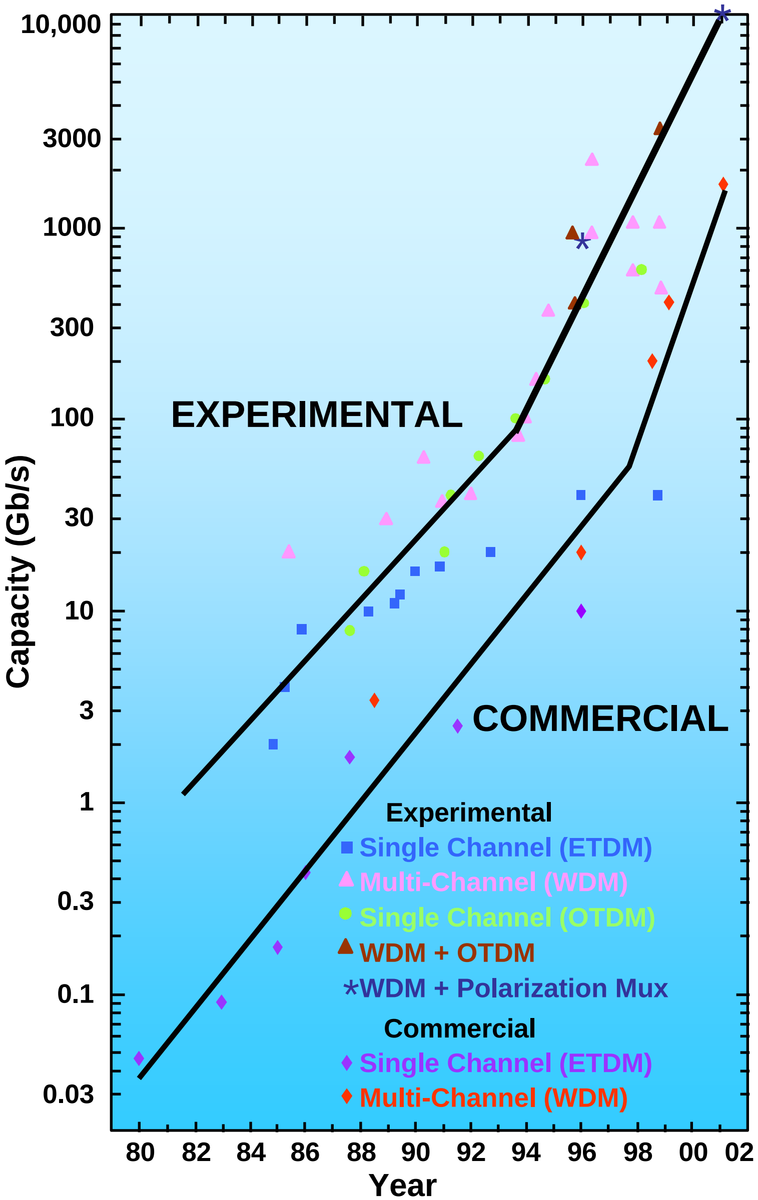
Optics Progress: Even Faster than Moore's Law!

10 YEAR IMPROVEMENT

IC Density : $\times$ **100**

Fiber Capacity: $\times$ ***200 !***



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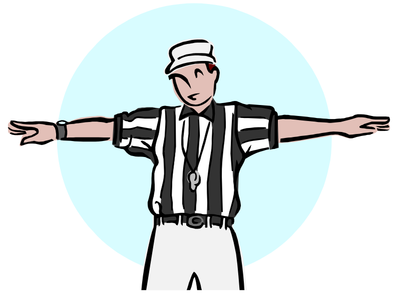


Get a Grip!

Capacity growth is not traceable to integration -

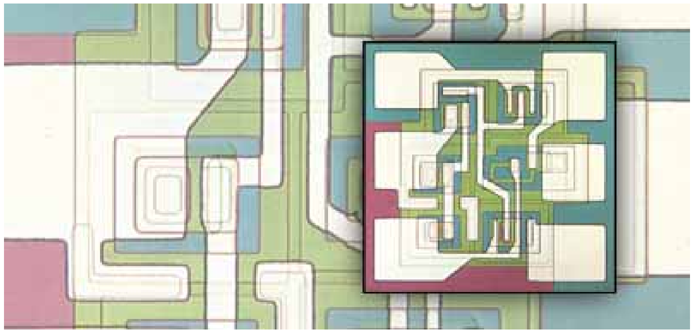
- **Photonic Integration offers promise of cost, power, size reduction**

however ….

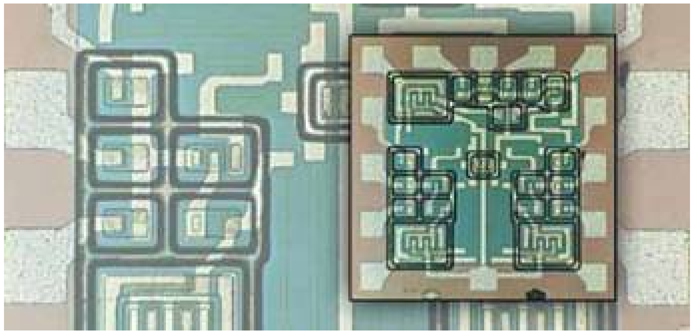
- **Massive, repetitive digital blocks in electronic IC's are truly, fundamentally, application enabling**

  ☞ ***Power of digital processing & especially software* in volume markets are drivers for Moore's Law**

So Turn Back The Clock, *reset our expectations …*



- **1964 early linear IC**
  - **- Matched actives & passives on chip**



- **1965 first commercial fully integrated OP AMP**

These analog circuits would not have driven Moore's Law & $B fabs … but they do target *clear volume applications* and are *powerful and enabling* in their reduced cost, size, and power!

Photonic Integrated Circuit Vision

Exemplary PIC with large variety of guided-wave elements:

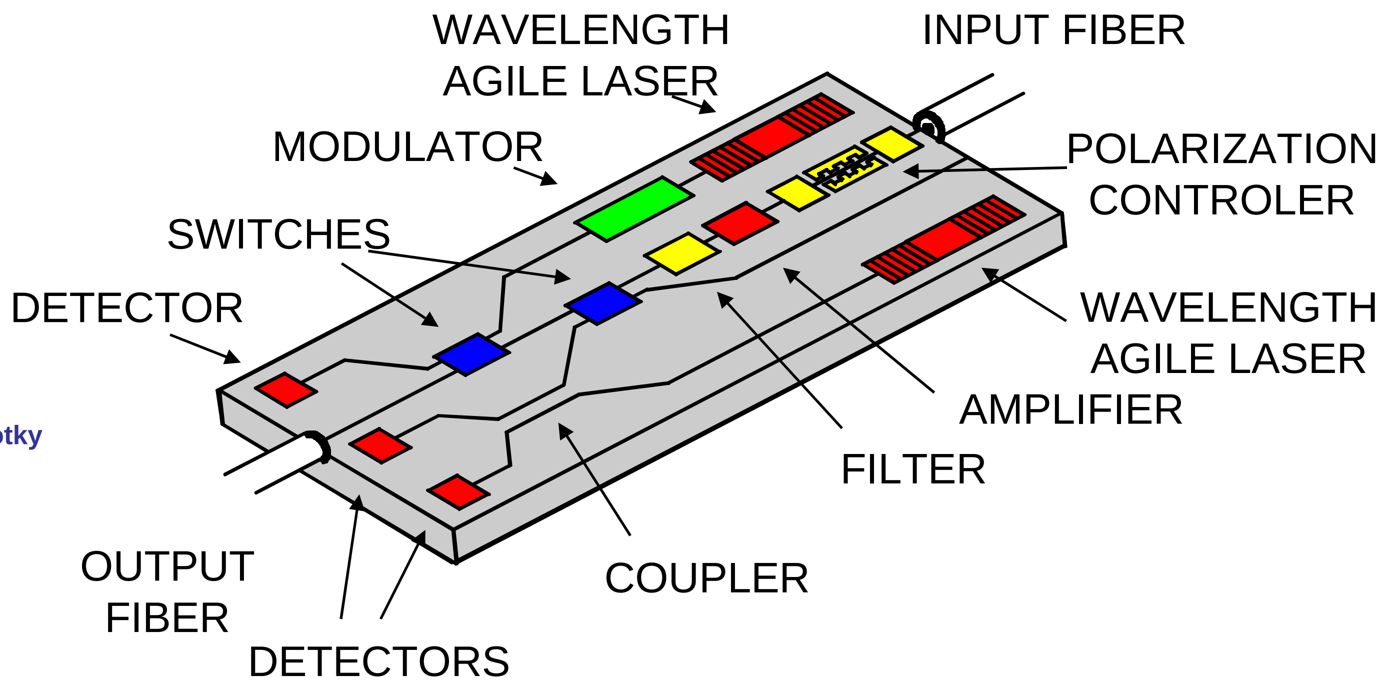
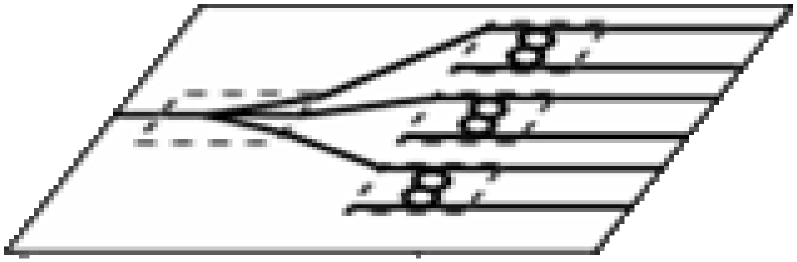
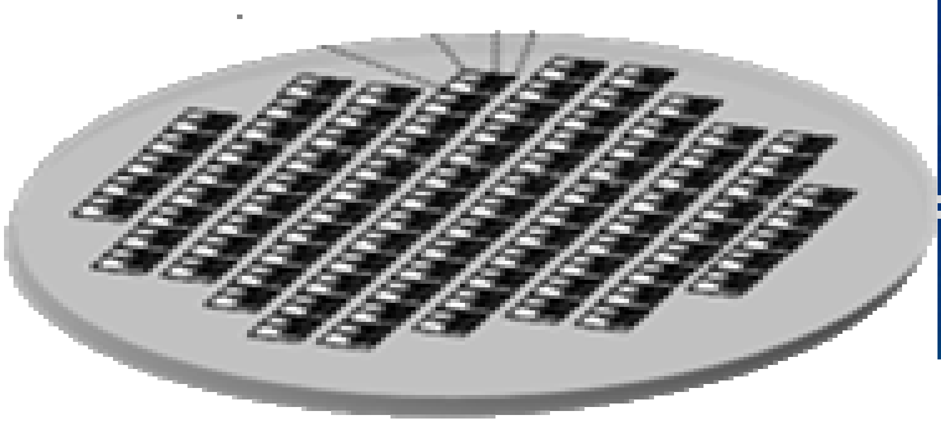


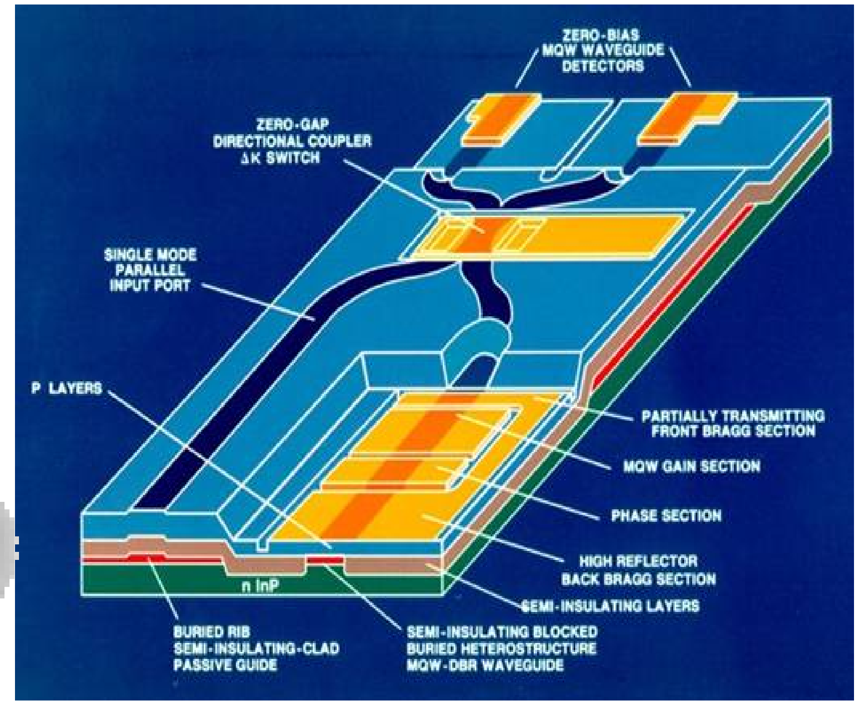
Fig. from S. K. Korotky

Monolithically interconnected optical and optoelectronic components fabricated on a common substrate

Why hasn't this taken off?







Monolithically Integrated Balanced Heterodyne Receiver PIC
Koch, et al PTL 2, 1990 p. 577

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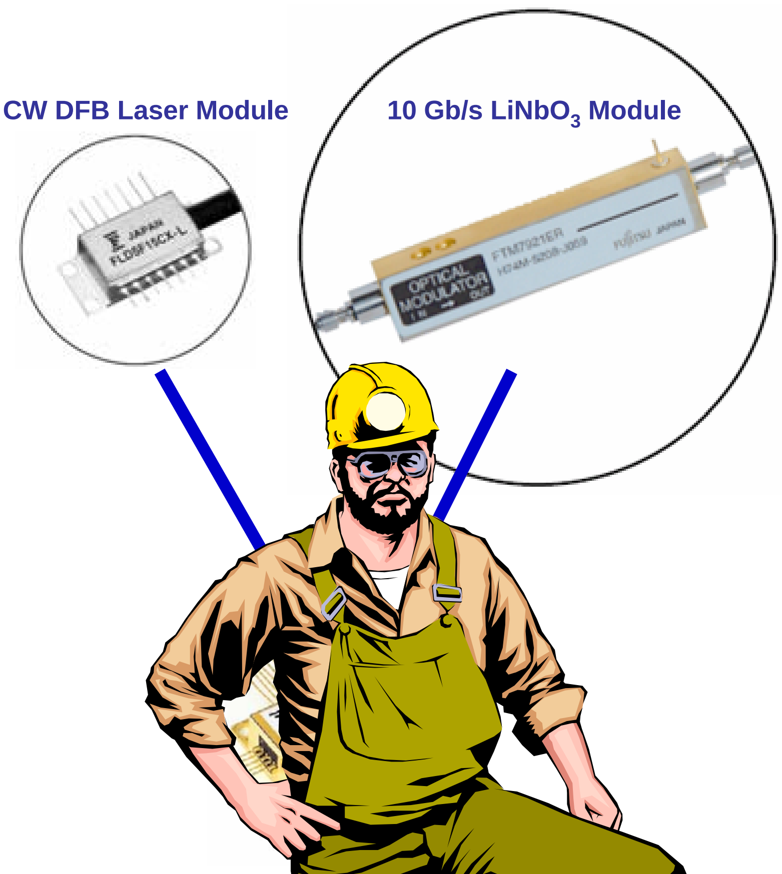
The Value Proposition:

The merits of integration

Systems vendors require reductions in cost, size, power; improvements in performance

When two or more elements are optically interconnected to form a functional subsystem:

- **we pay for two or more packages** ***(packaging can be 50-80% of cost, even more compelling than IC's!)***
- **we get larger subsystems; devices constrained to use long optical paths**
- **we lose power from fiber coupling efficiencies (lower SNR)**
- **we incur instabilities or fluctuations from coupling – efficiency, phase, reflections …**



10 Gb/s Integrated Modulator Laser Module Using InP-based PIC

Can these be so dramatic as to be market enabling?

- ultimately yes, but in the near term we have …

The challenging work of implementing a replacement technology!

What needs to be integrated …

Two kinds of replacement technology…

- Replacing discrete optical solution & offering improvements in cost, size and/or power.

- Replacing FUNCTIONALITY previously done with electronics using optical networking architectures and optical technologies

But there's also some subtlety …

Two kinds of replacement technology…

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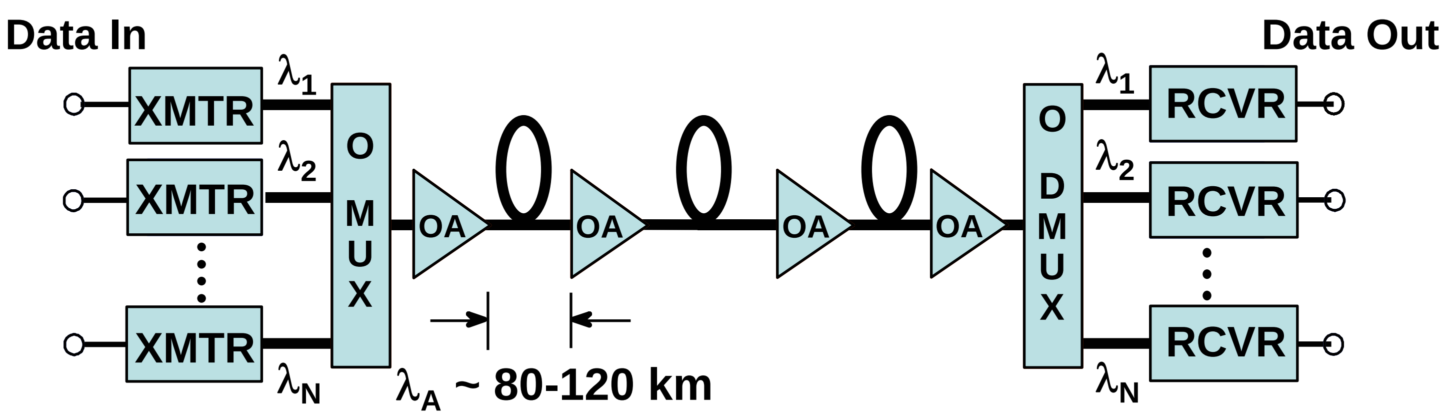
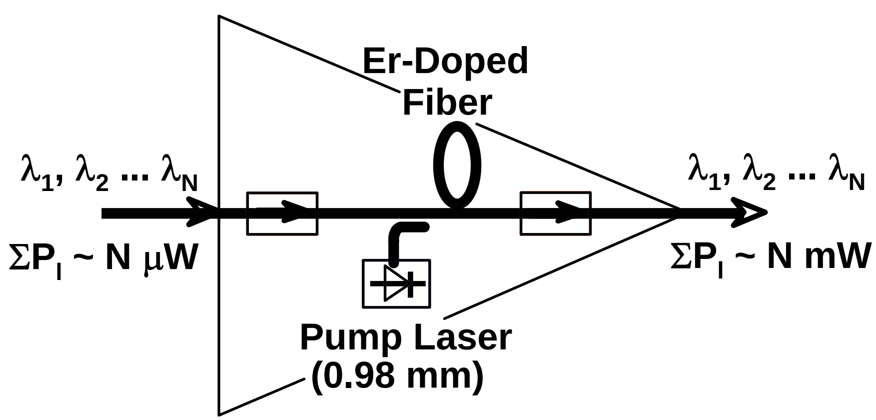
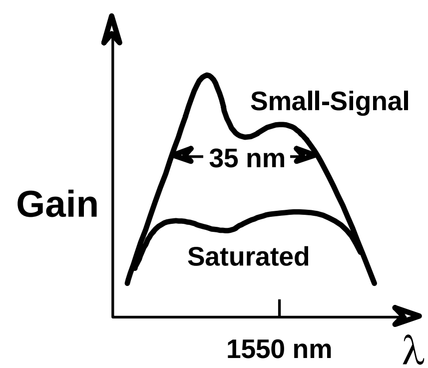
Optically Amplified WDM Transmission System



Amplified (Non-regenerated) Transmission Line



Erbium-Doped Fiber Amplifier



Gain Spectra

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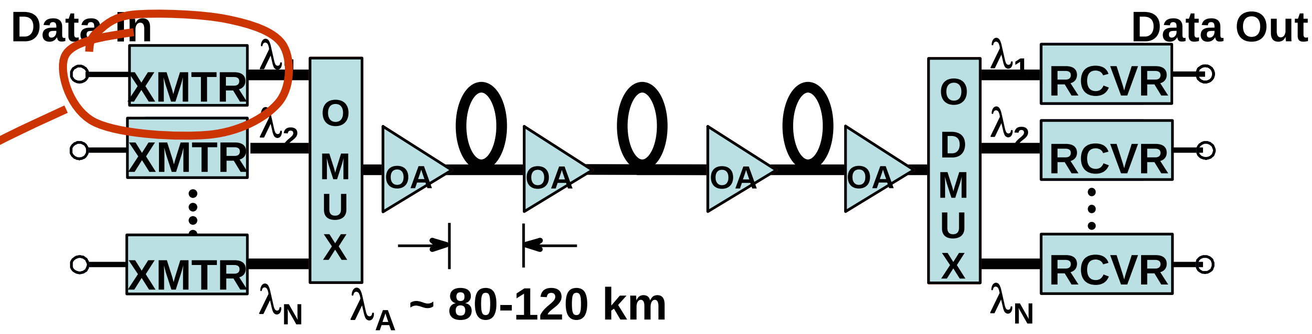
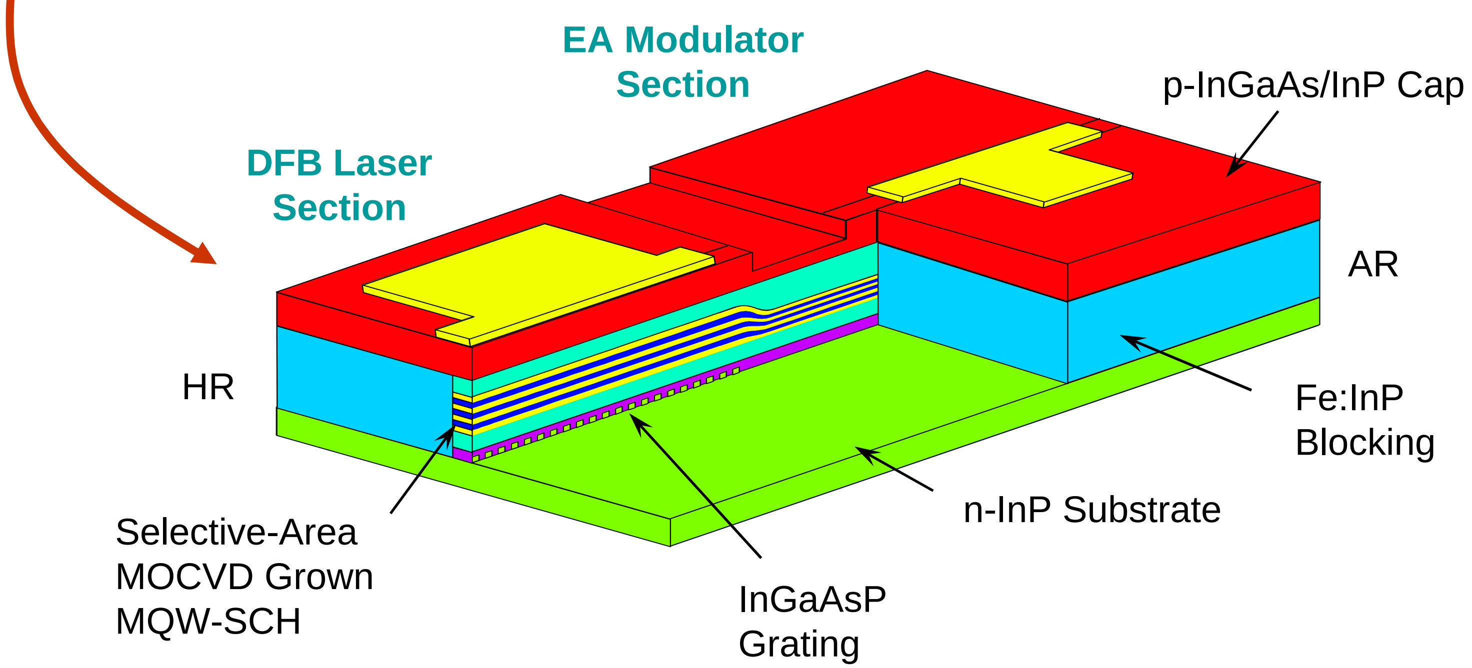
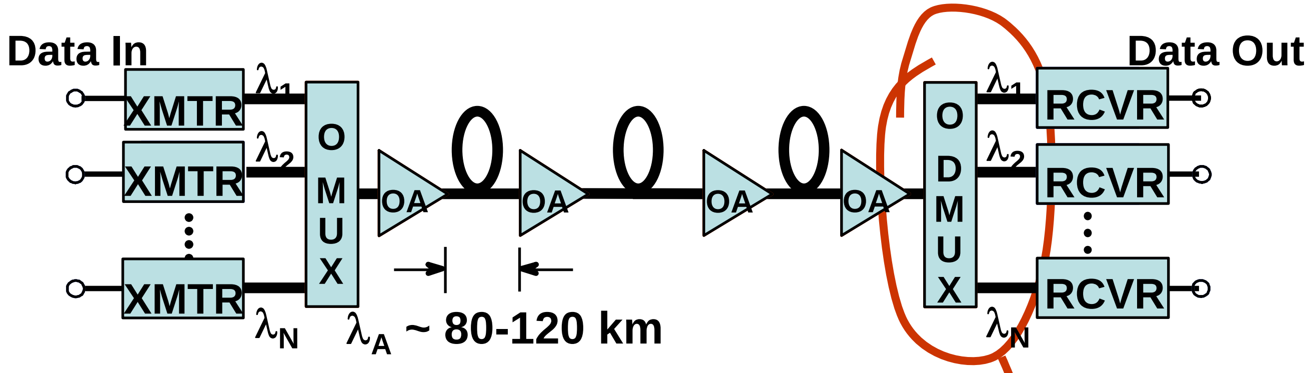
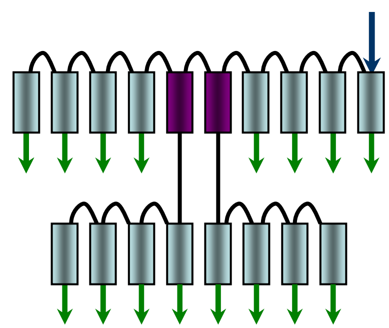


Integrated DFB Laser/EA Modulator by SAG



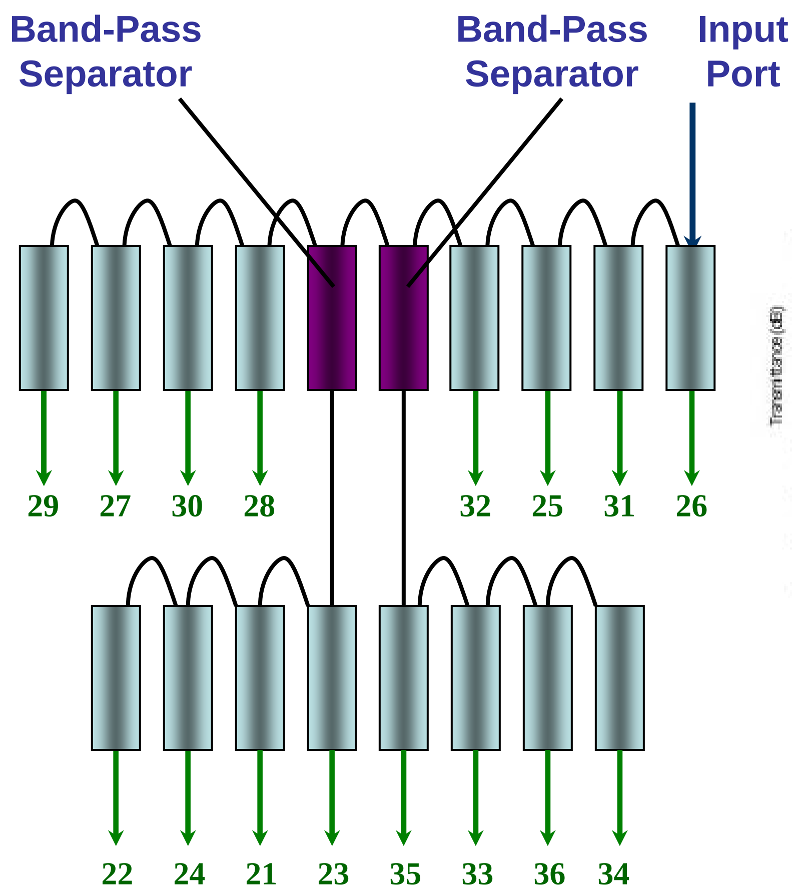


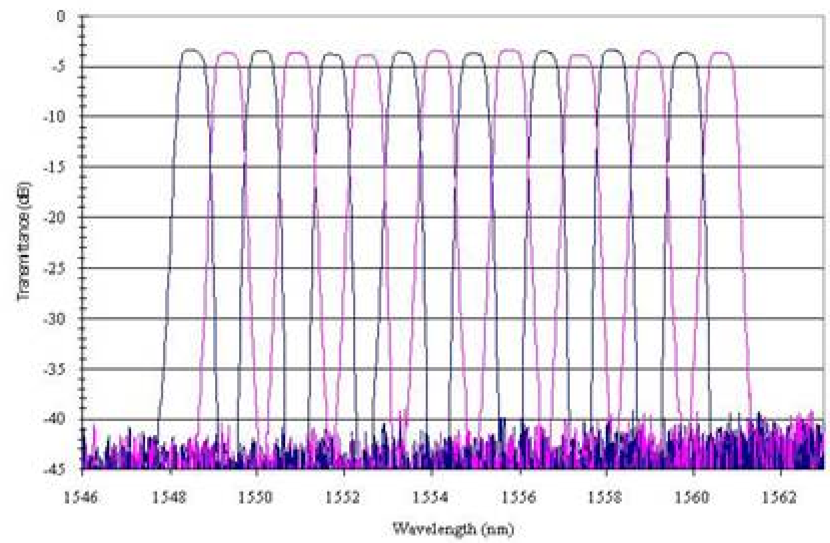
What about the receive demux side?



Discrete solutions:
Cascaded Thin-Film
Filters

Typical TFF Demux Configuration
Ex: 100 GHz 16-Channel





What about 160-channel?

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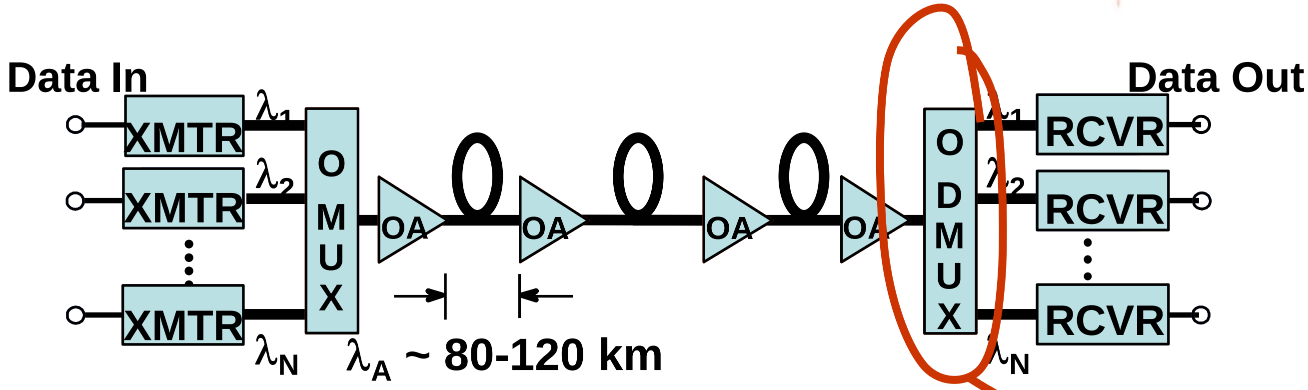
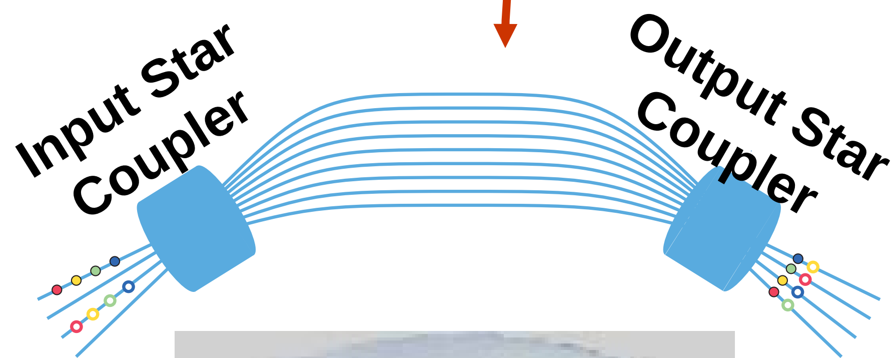


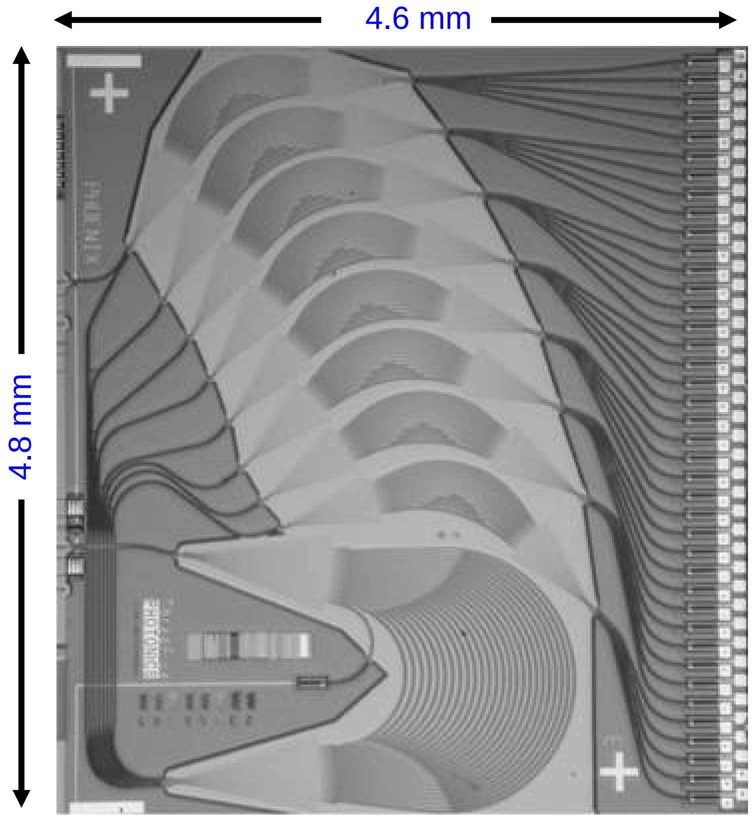
Si/SiO_2 Waveguide Grating Router:

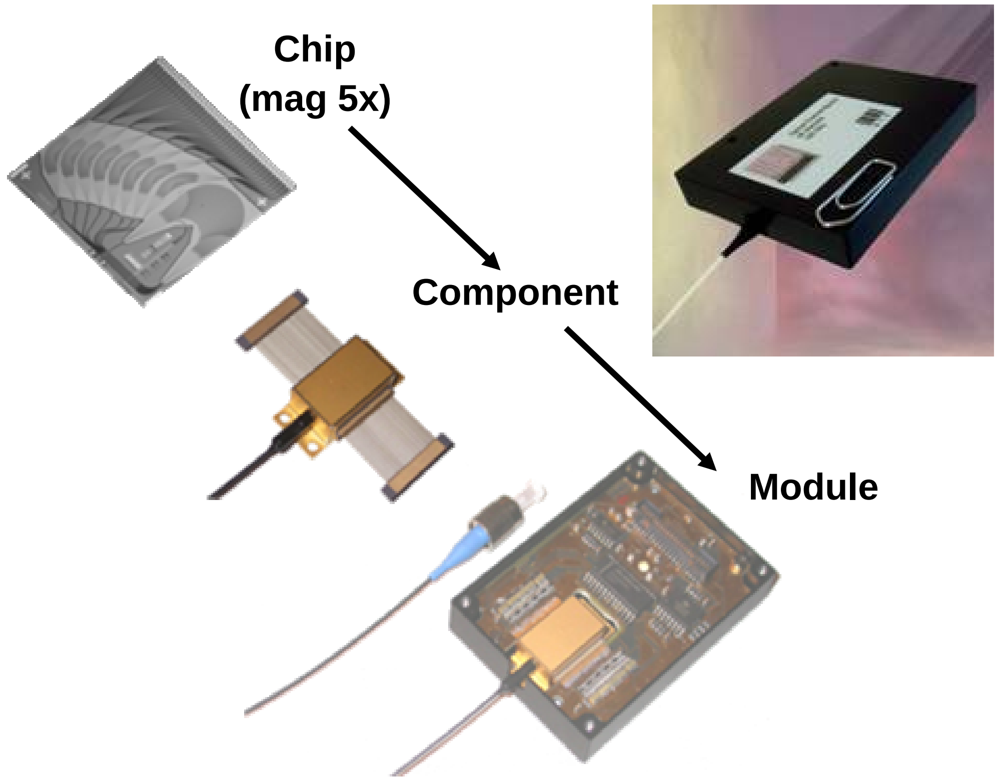
- Readily scalable to large channel count
- Wafer scale processing
- Stable, inexpensive optical interconnections



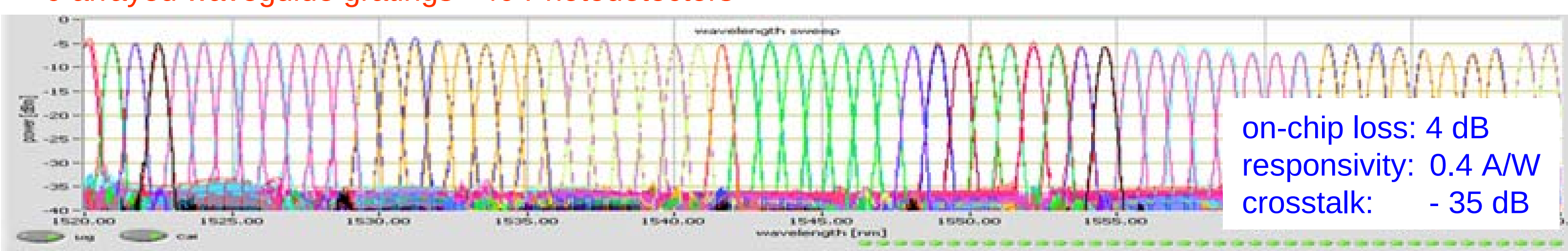
Today's technology for WDM integration:

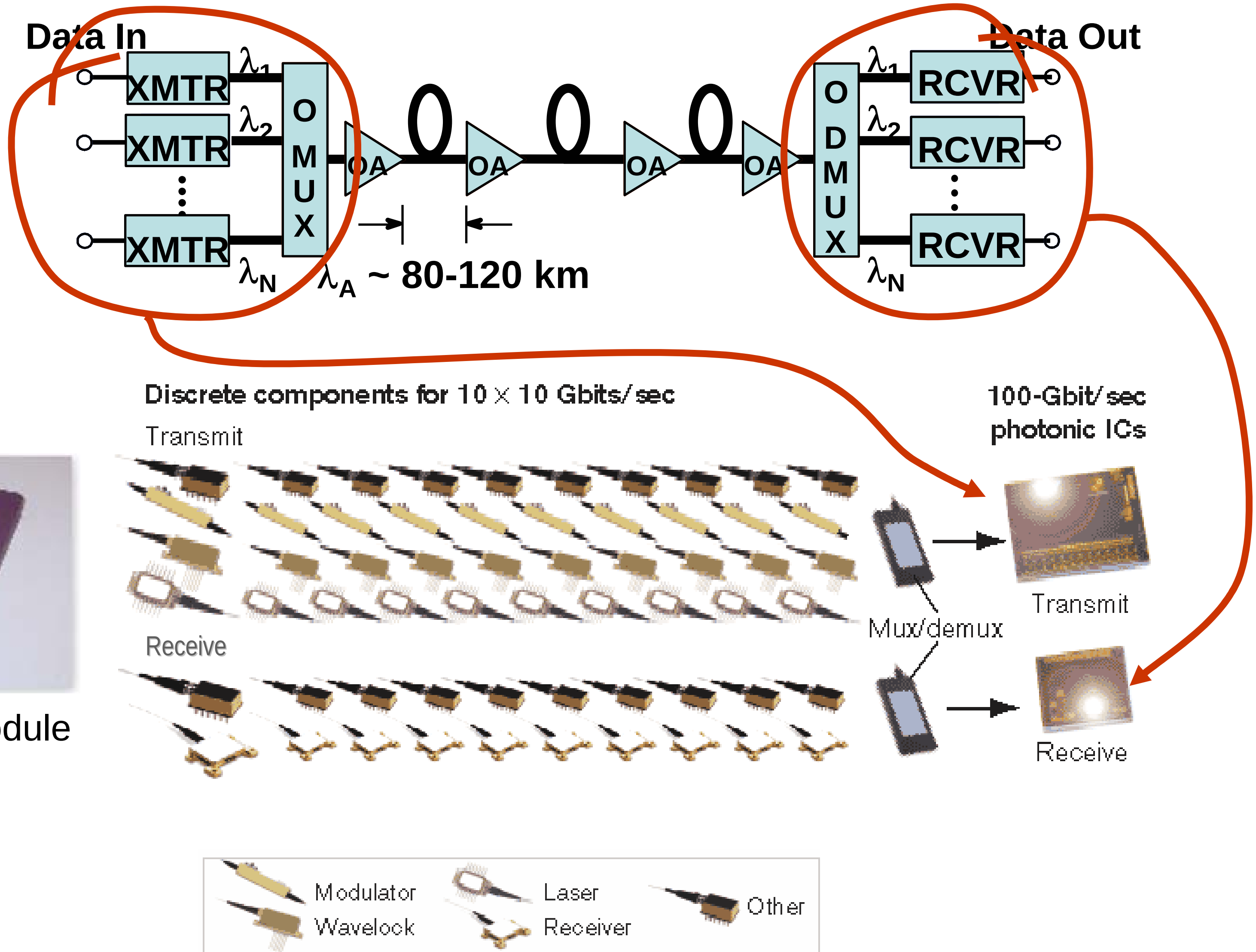
World's smallest integrated AWGs: 40 channels integrated

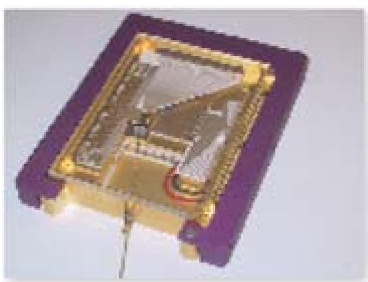




9 arrayed waveguide gratings+ 40 Photodetectors







Packaged Module

But there's also some subtlety …

Two kinds of replacement technology…

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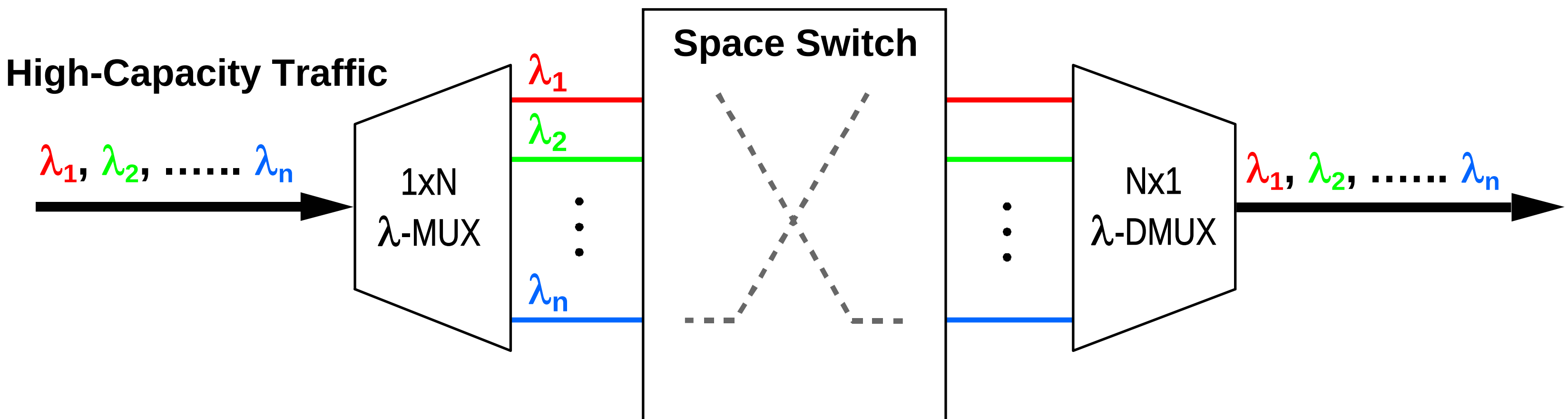
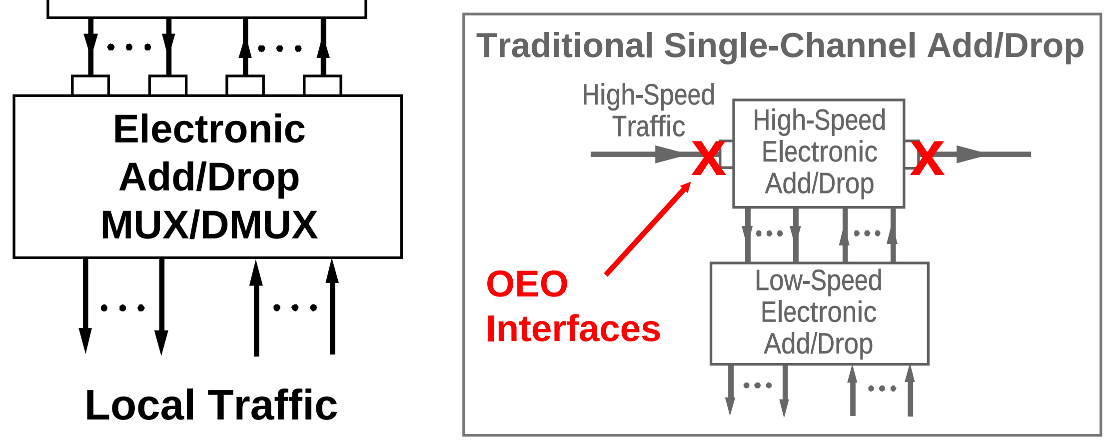
RECONFIGURABLE ACTIVE WDM ADD/DROP





- Reduced cost dynamic provisioning at λ granularity without full OEO

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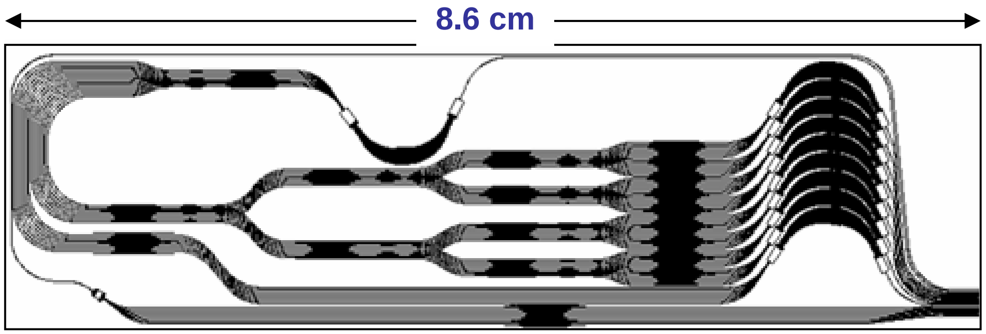
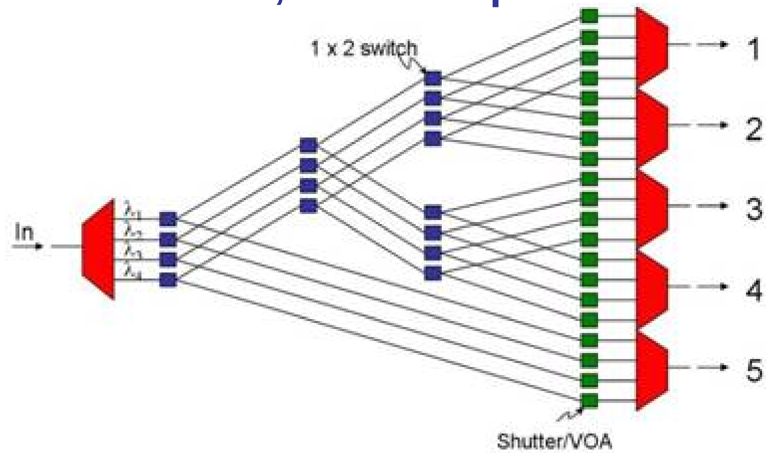
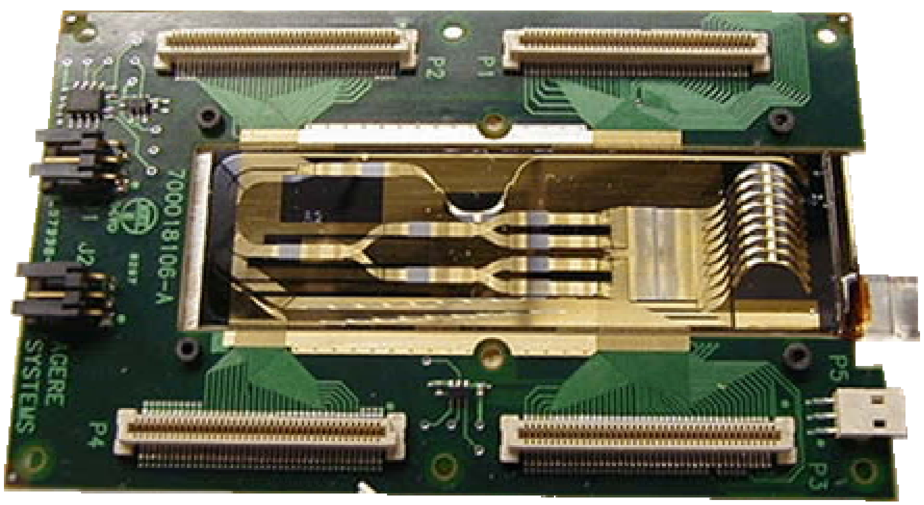
8-λ 1 × 9 Wavelength Selective Cross-connect

Doerr et al, Bell Labs



4λ, 1x5 example



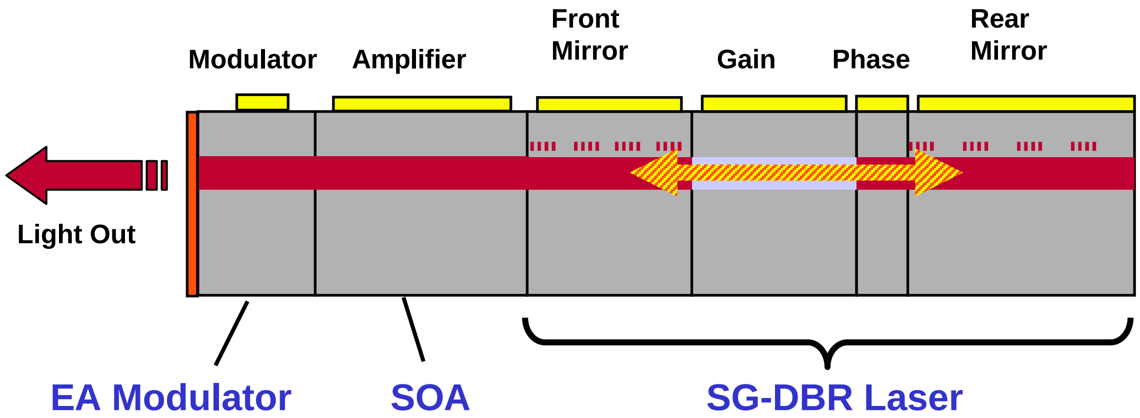


Features:

- 64 switches, 80 shutter/VOA's
- Any λ to any port
- All paths have double rejection in both space and wavelength
- Smaller and fewer activated switches than classic split-and-combine

Advantages of Monolithic Integration

- **Widely Tunable SG-DBR Laser with integrated SOA and EAM**



Advantages:

- **smaller space (fewer packages)**
- **lower cost (fewer package components)**
- **lower power consumption (lower coupling losses)**
- **high reliability (fewer parts)**

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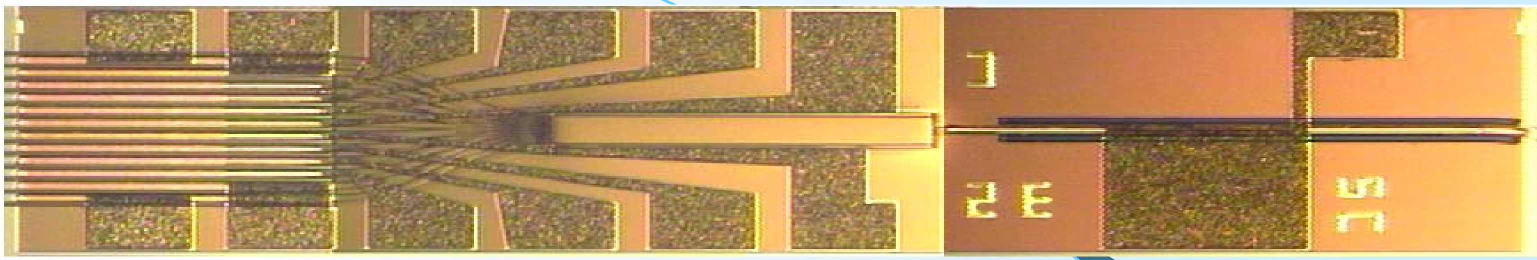
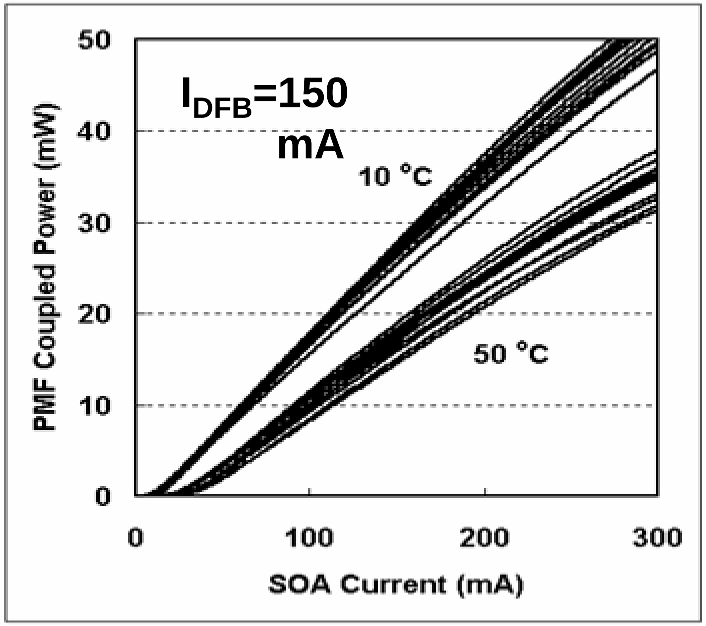
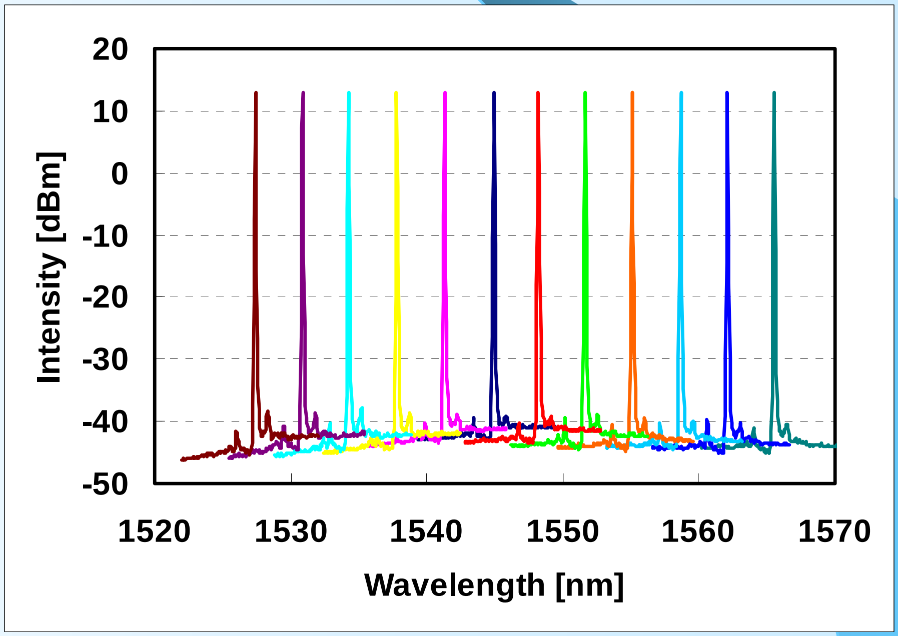
We can.

Full C-band, high power wavelength selectable laser



1 x 12 DFB   S-Bent   MMI   SOA





PMF output power
> 30 mW at T_{LD}=50 ° C

- SMSR > 50 dB
- $\Delta\lambda$=3.5 nm, σ < 0.1nm
- Tunability ~ 40 nm

(reported in ECOC'2003)

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Optical ASICs

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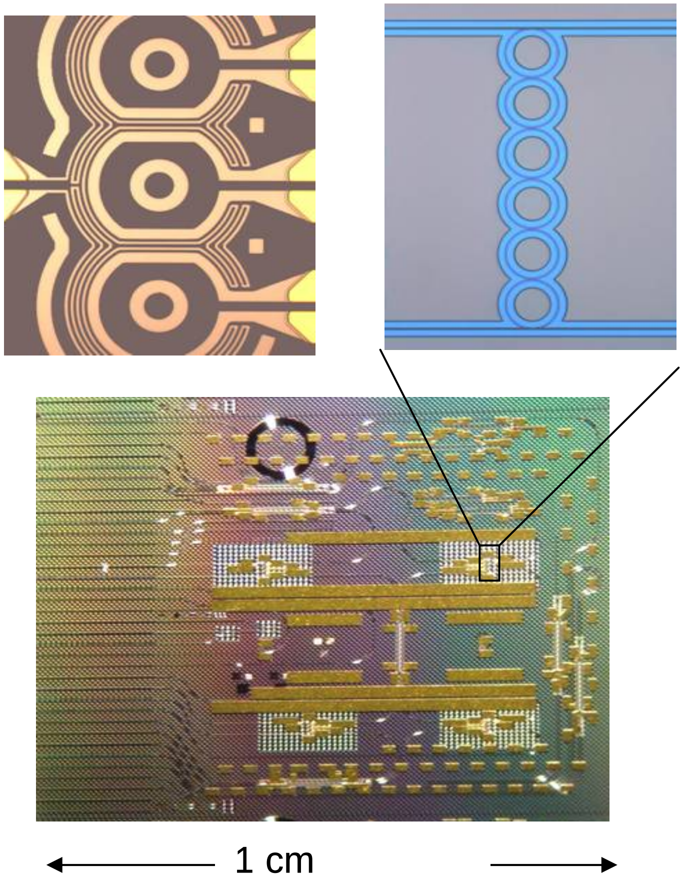
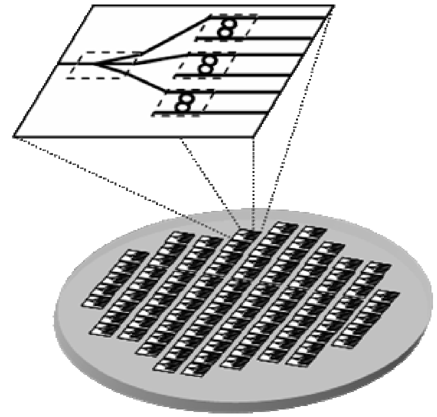
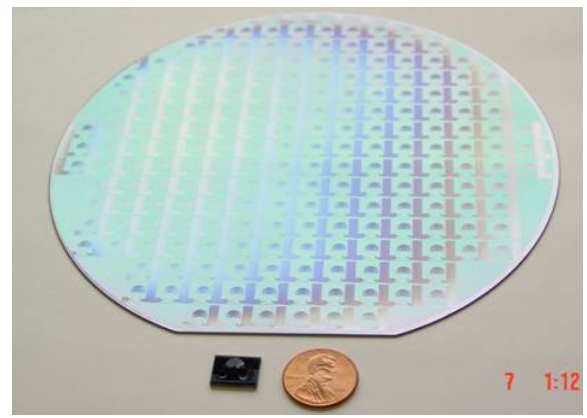




Little Optics



Dense Functionality on a Chip

(Tunable High order microring resonators, switches, VOAs, polarization beam splitters, polarization rotators, mode transformers, delay lines, all pass filters)

High Volume Batch Fabrication

(Hundreds of chips per wafer)

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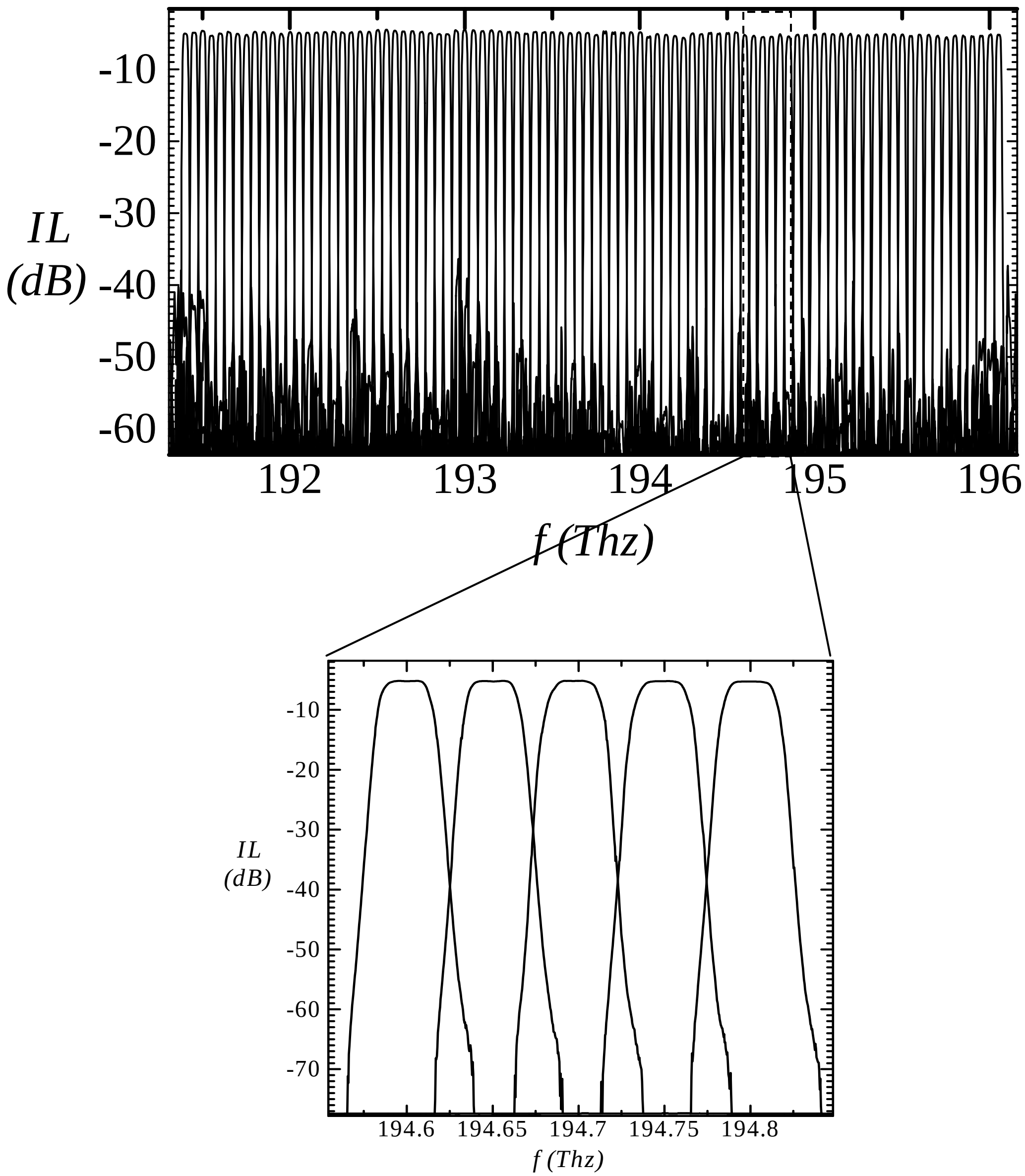
High Performance & Functionality



Channels	= 100
Avg IL	= 4.1 dB
Avg PDL	< 0.5 dB
Avg 1 dB BW	= 28 Ghz
Avg 3 dB BW	= 33.0 Ghz

Full C-band (or C+L) Tunable Filters

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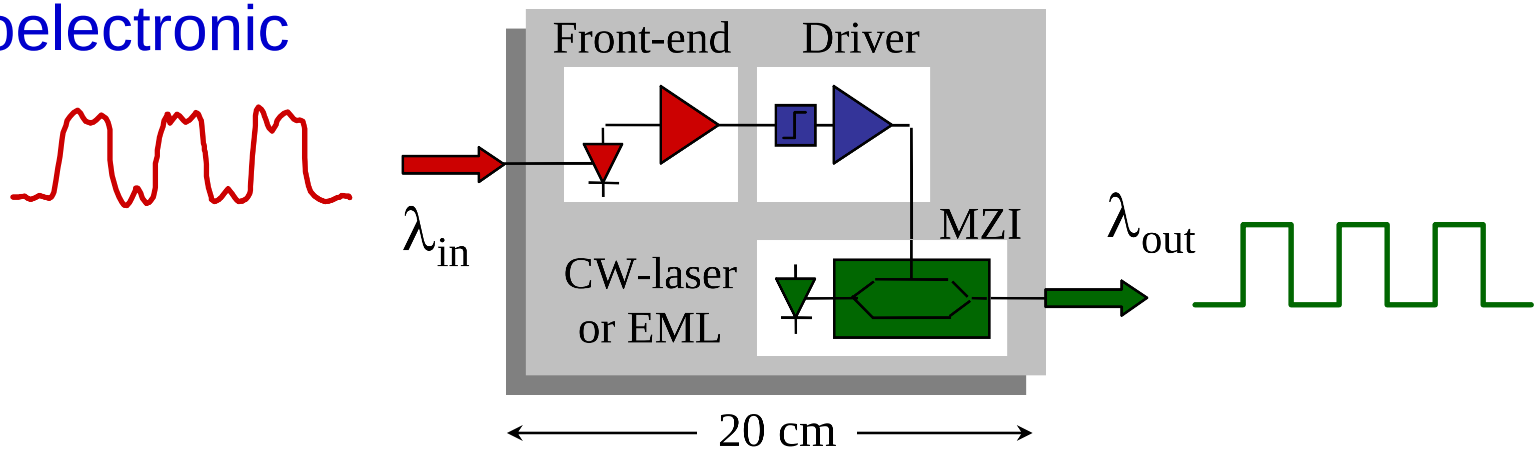
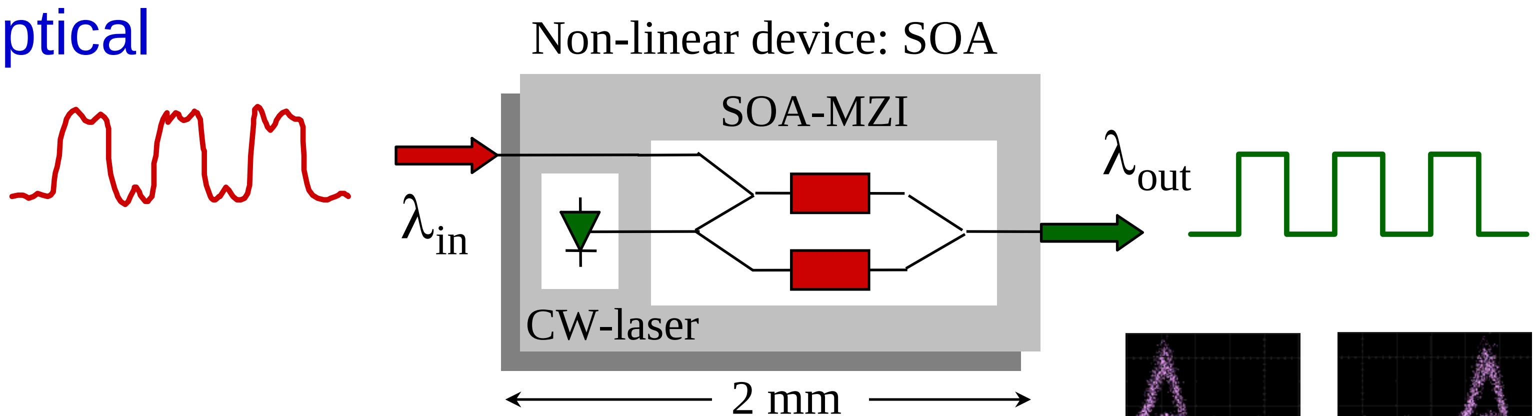
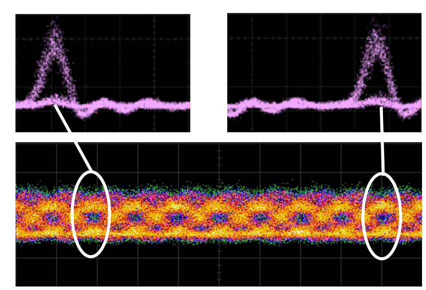
Optical regeneration

Optoelectronic



All-optical





Similar techniques have worked at speeds to 160 Gb/s!

Resonant-Enhanced Functionality:

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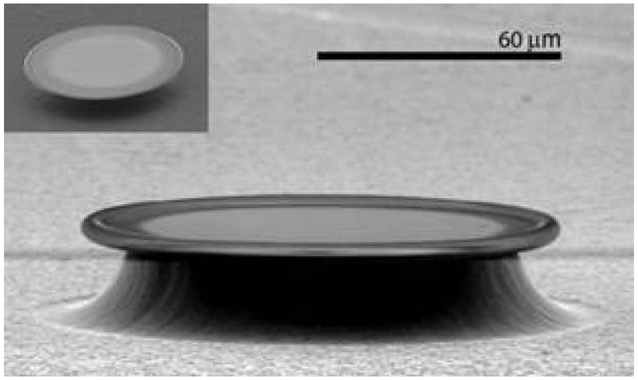
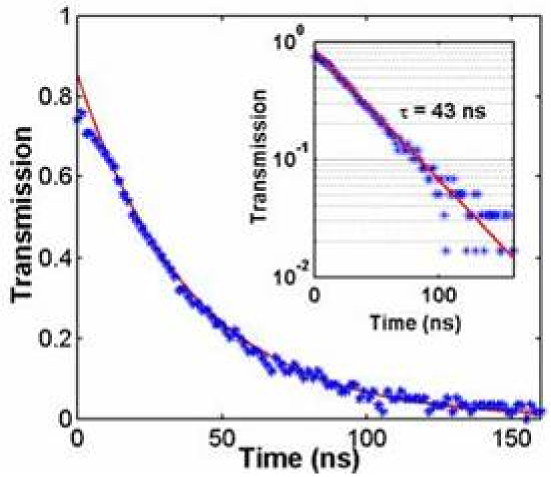
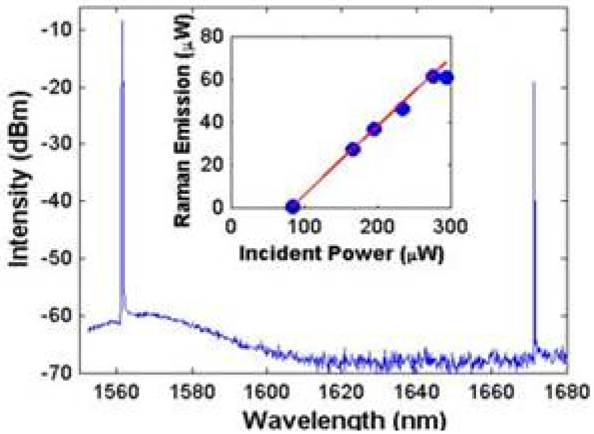
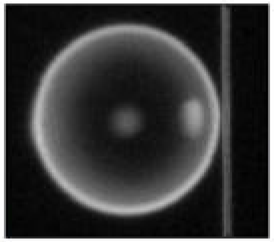
Vahala et al, Caltech





- **Q's of 10^8 !!**
- **Raman & parametric oscillators, amplification in µ-resonators**
  - **- SiO_2-based resonators**
  - **- Extend to Si-based resonators? (i.e., SOI) *Need ultra-low loss!***





Single longitudinal mode Raman lasing in a 40-µm diameter microsphere, exhibiting 16% pump conversion. Inset: η_d = 36%.

Think analog IC's & microwave mixing techniques

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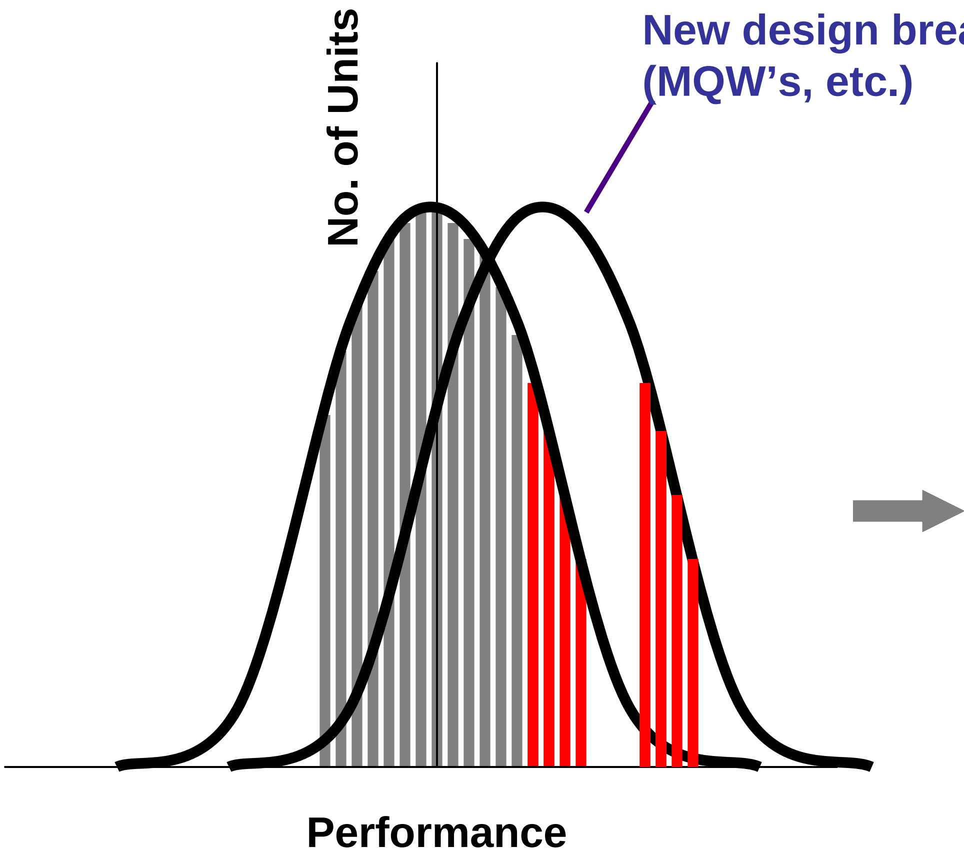
Yield & Performance



Why does this happen?

- **Huge leverage in core of network for incremental improvements in performance**
- **High willingness to pay due to tremendous cost sharing**
- **That was then, *this is now …***

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Today's Market Realities …

- Severe pressure on service providers; fighting for piece of limited disposable income in the face of escalating bandwidth & connectivity!
- New deployment targets:
  - Larger relative investments in metro & access
  - Less ability to share cost at edge of network
  - Systems houses less likely to pay for marginal increases in performance (standardization)
  - All asking for dramatic reductions in cost, size, power (really cost, cost, cost)
- ***Photonic Integration can deliver what today's market is asking for***

Important future directions:

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- Drive refinement, stabilization of process technologies
  - in III-V's, refine use of QWI, more planar process technologies
  - reliable process/device/integration modeling tools on stable platforms
  - piggyback on CMOS, explore functionality of Si and SOI
  - for passives, push limits of high-index-contrast integration
  - true integration with CMOS electronics
- Packaging of photonic IC's
  - RF & thermal challenges of high-density; I/O bottlenecks
  - better array solutions; passive or MEMs alignment
- Really understand cascadability of active functionality
  - Limits of 2-R, 3-R regeneration, ultrafast nonlinear SOA dynamics
  - Power consumption, density limits, noise
- Drive ultra-low loss fab techniques; understand potential of ultra-high Q resonant structures
  - nonlinear functionality (Raman, parametric)
  - highly cascaded passives
  - higher-density integration

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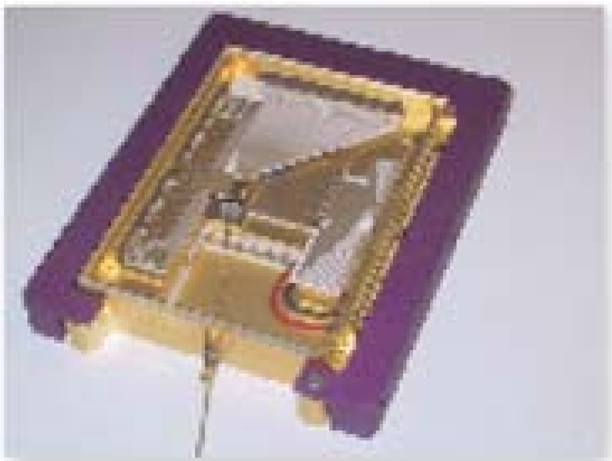
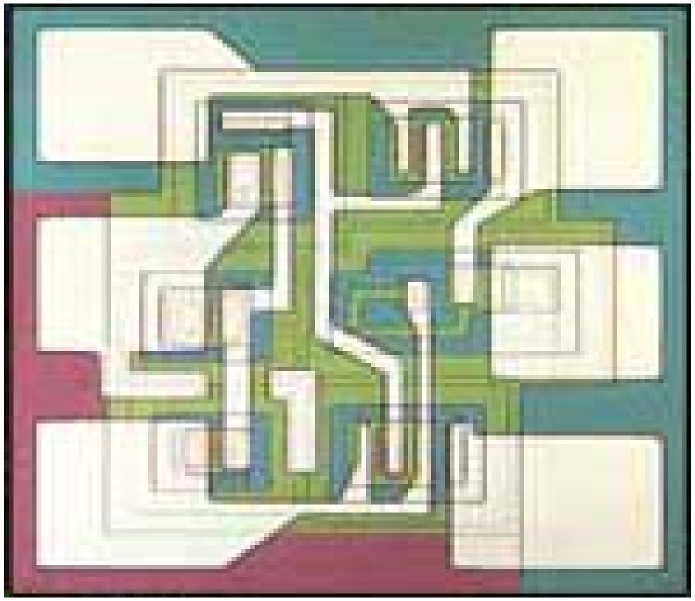
For the naysayers …..

infinera





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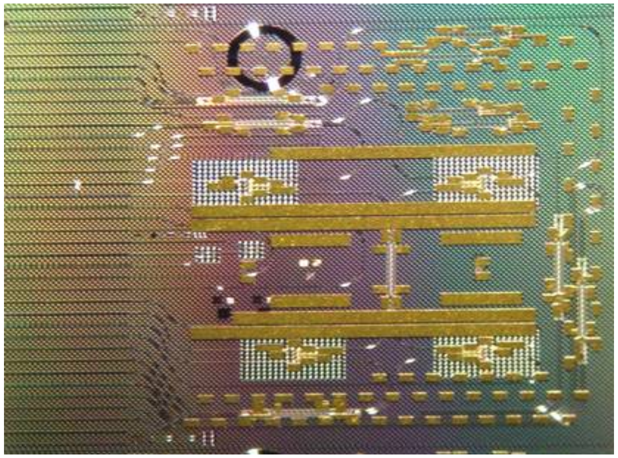

Already exceeding complexity of 1st generation analog IC's!