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Center for Optical Technologies

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**

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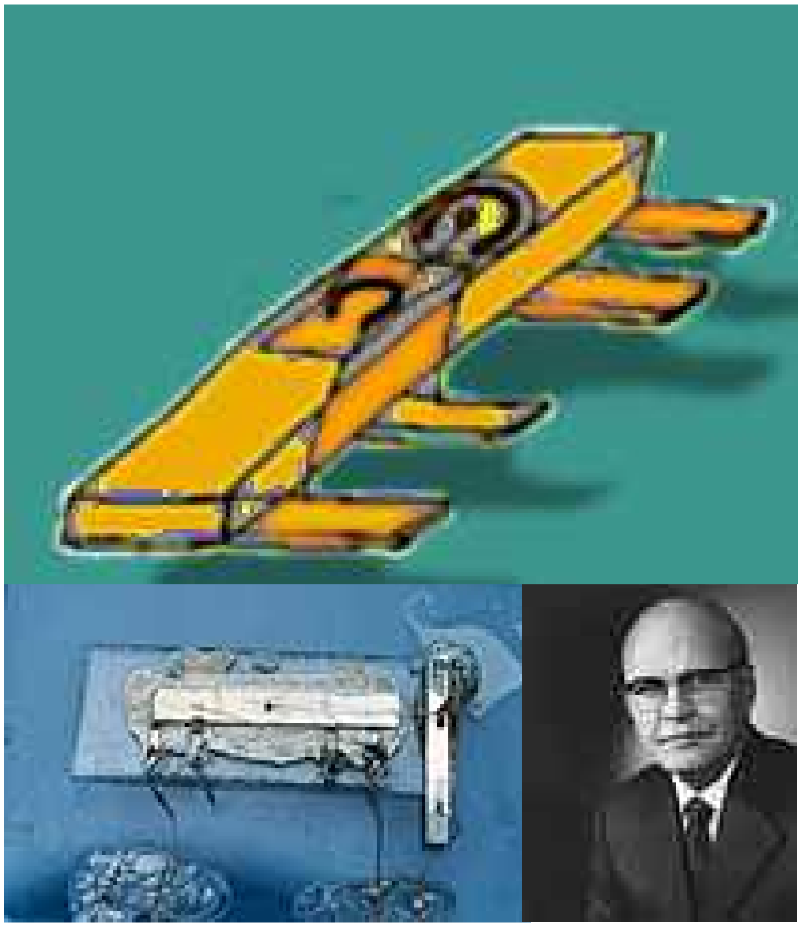
The greatest story of Integration …



- 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 …

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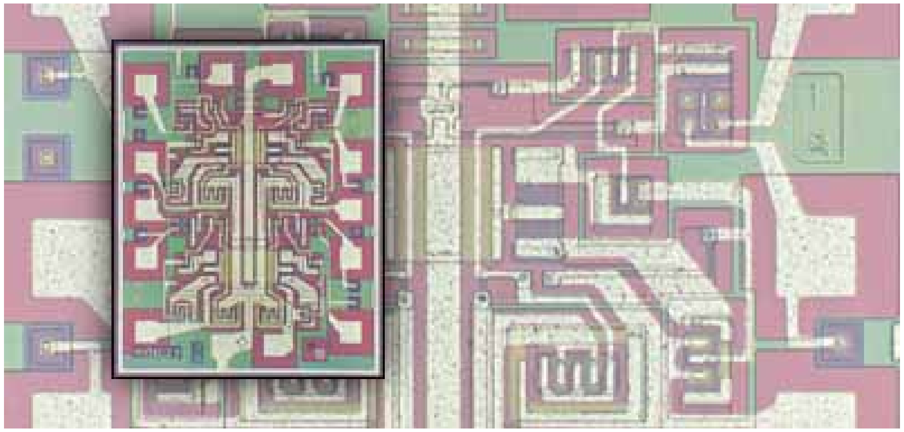
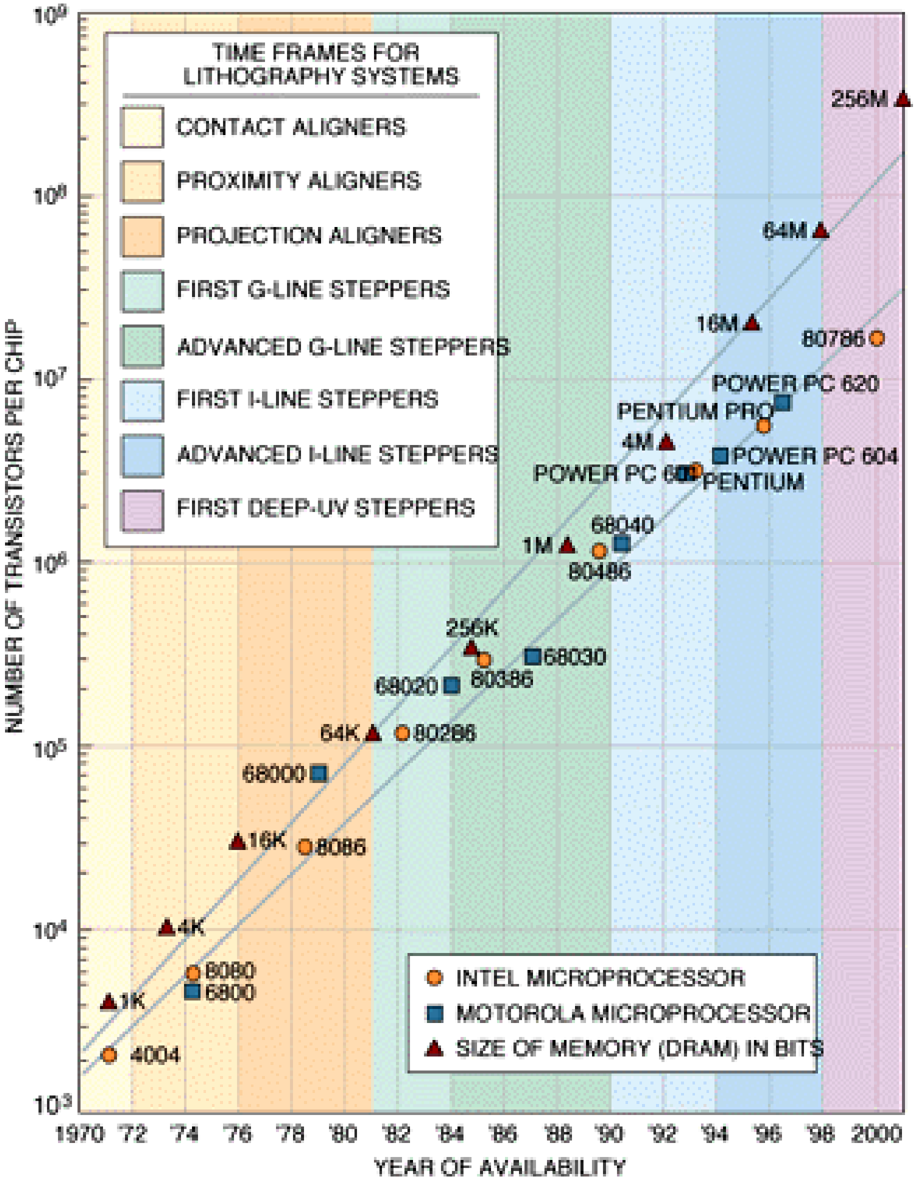
The Digital Revolution Ramps Up!

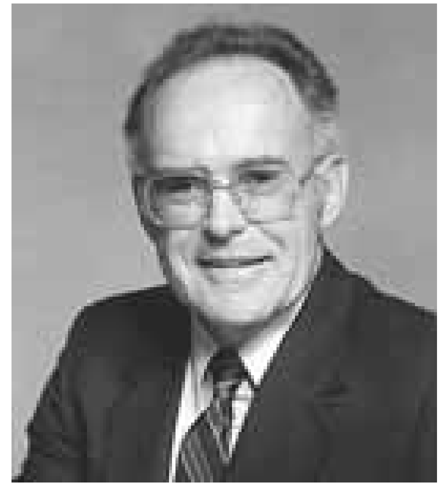


1966 TTL logic chip

- 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

Relentless Advance of IC Integration





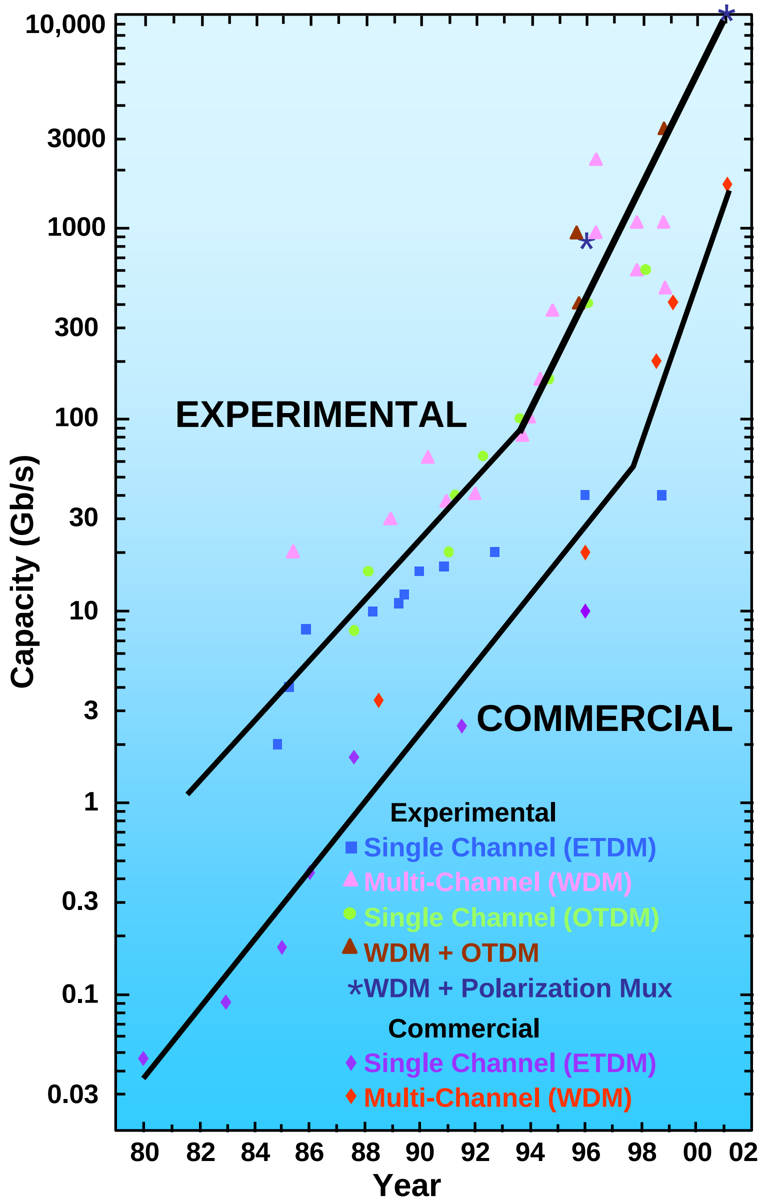
- Moore's Law (1965)
- Doubling in # of transistors every 18 months (60% CAGR)
- Example (close to true!):
  - 1965 most complex digital chip had 64 transistors
  - 2000 intro of Pentium IV processor w/est. 42 million transistors
  - DRAM tracking also

Optics Progress: Even Faster than Moore's Law!

10 YEAR IMPROVEMENT

IC Density : × **100**

Fiber Capacity: × ***200 !***



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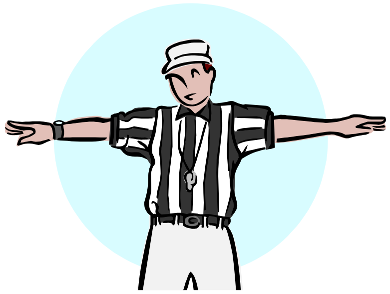


Get a Grip!

Capacity growth is not traceable to integration -

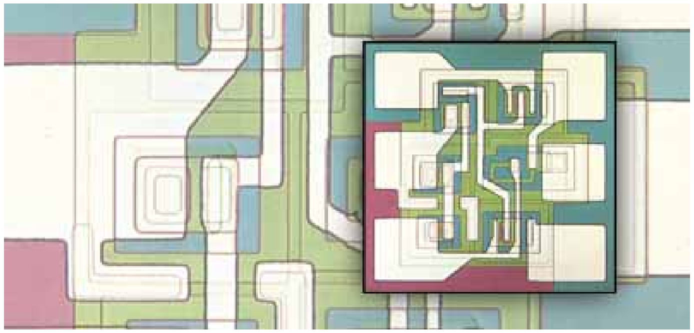
- **Photonic Integration offers promise of cost, power, size reduction**

however ….

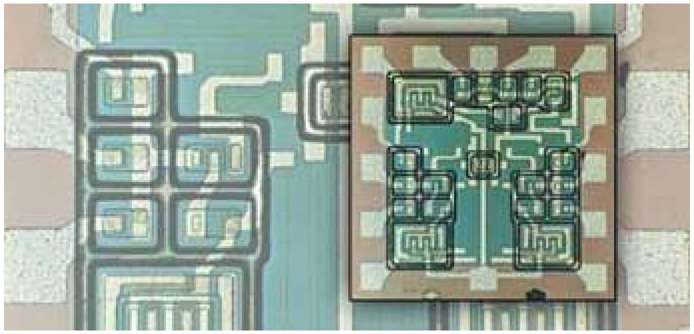
- **Massive, repetitive digital blocks in electronic IC's are truly, fundamentally, application enabling**

☞ ***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!

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Photonic Integrated Circuit Vision

Exemplary PIC with large variety of guided-wave elements:

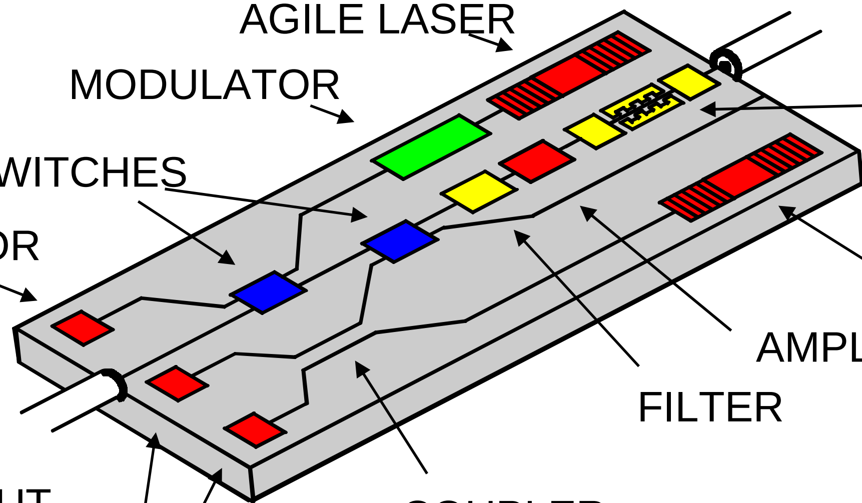
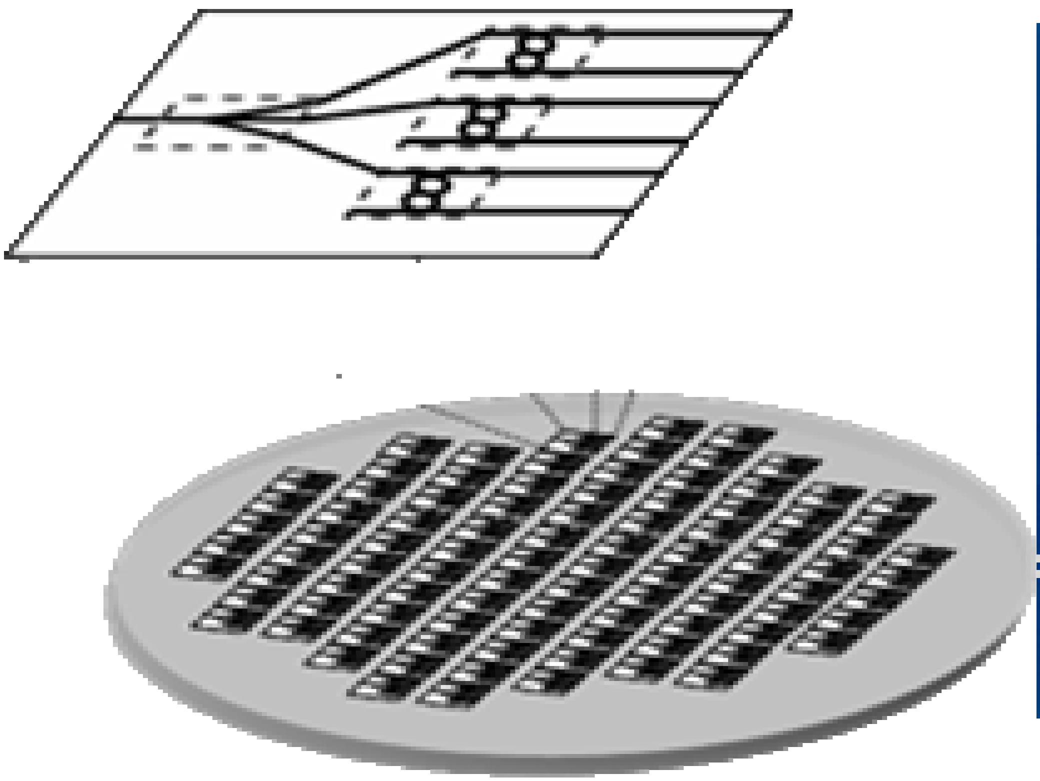
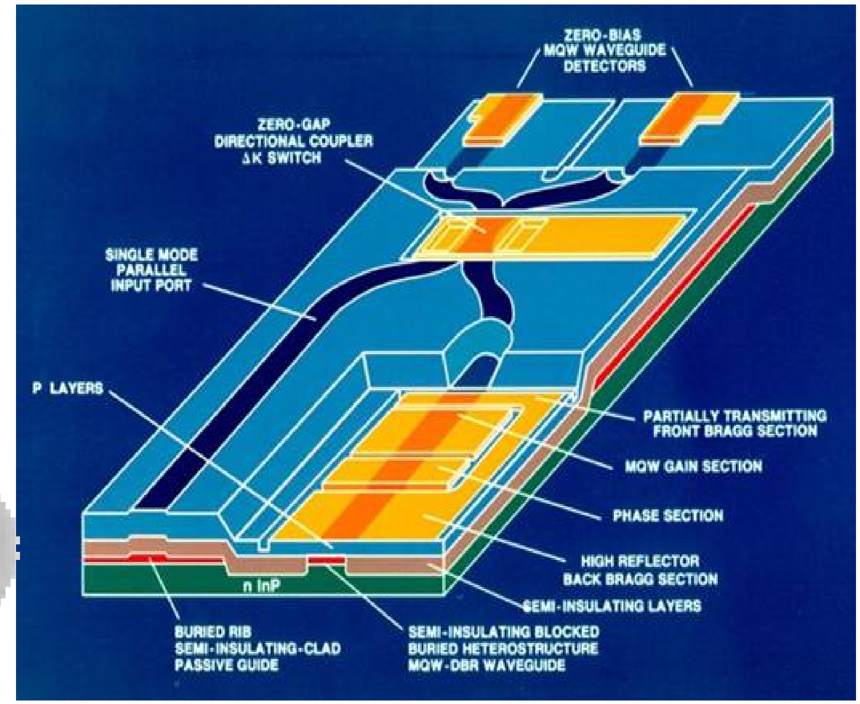


Fig. from S. K. Korotky

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

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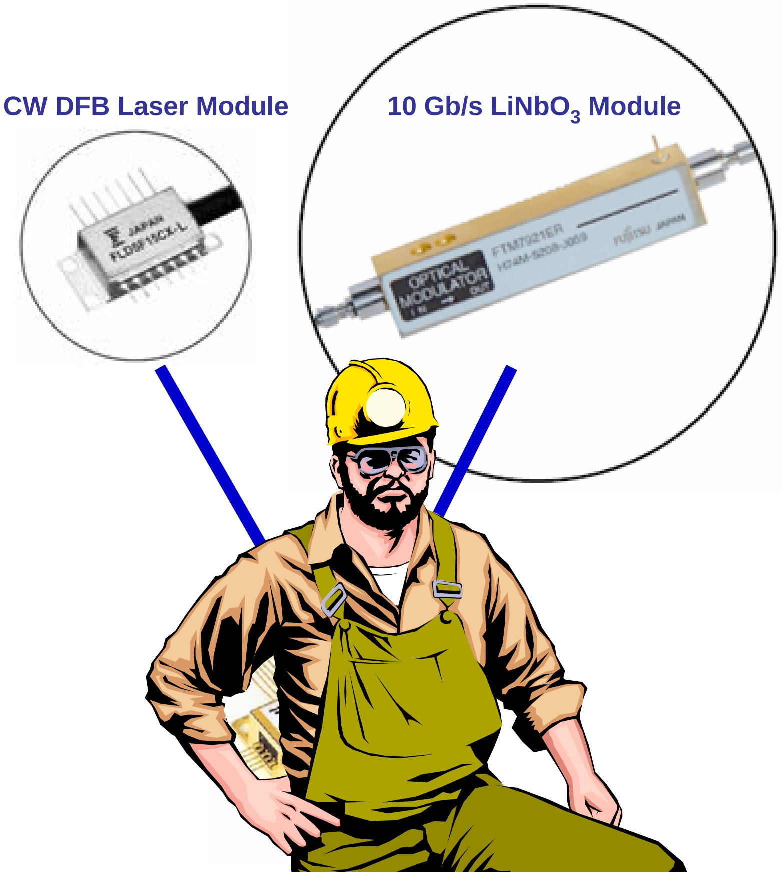
Systems vendors require reductions in cost, size, power; improvements in performance

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 …**



Can these be so dramatic as to be market enabling?

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

- 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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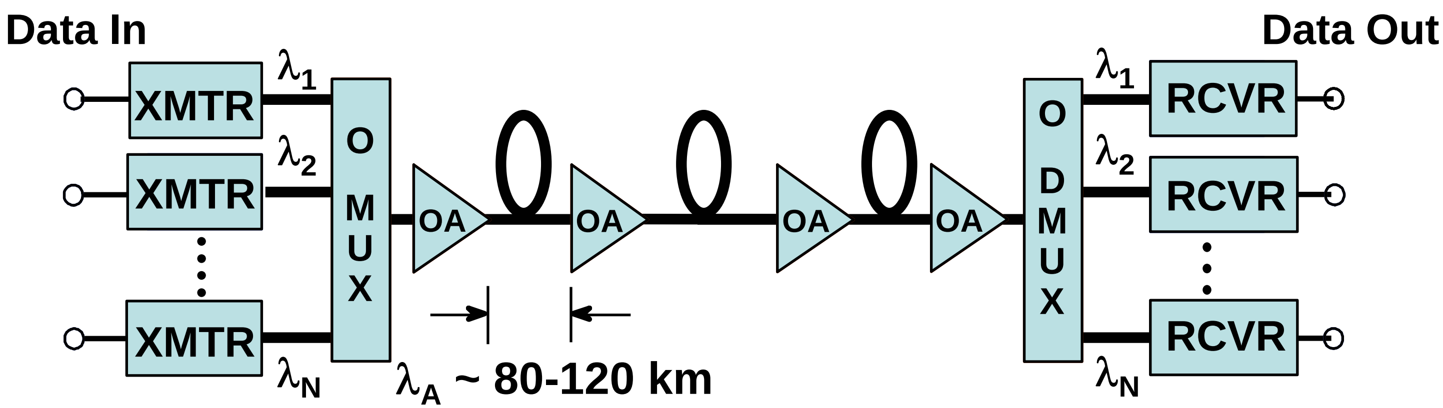
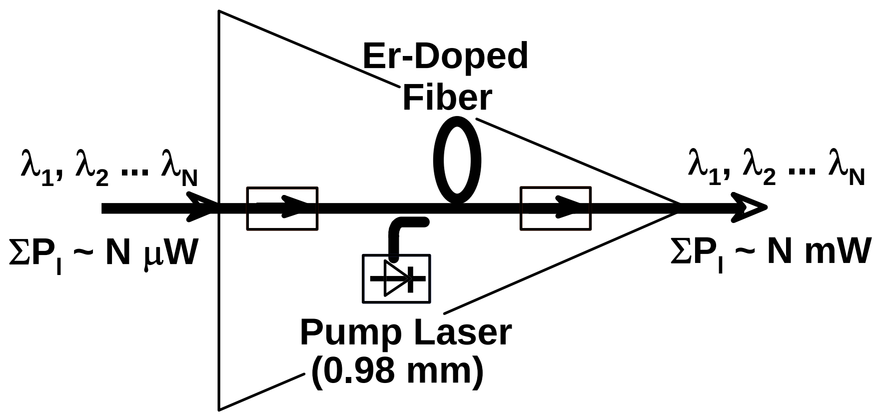
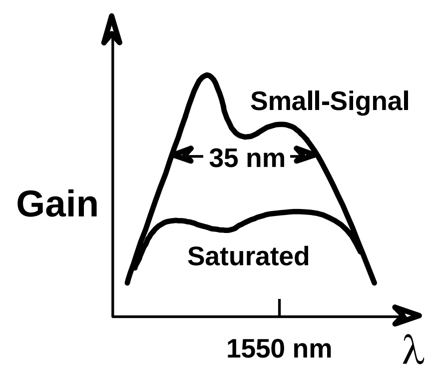
Optically Amplified WDM Transmission System



Amplified (Non-regenerated) Transmission Line



Erbium-Doped Fiber Amplifier



Gain Spectra

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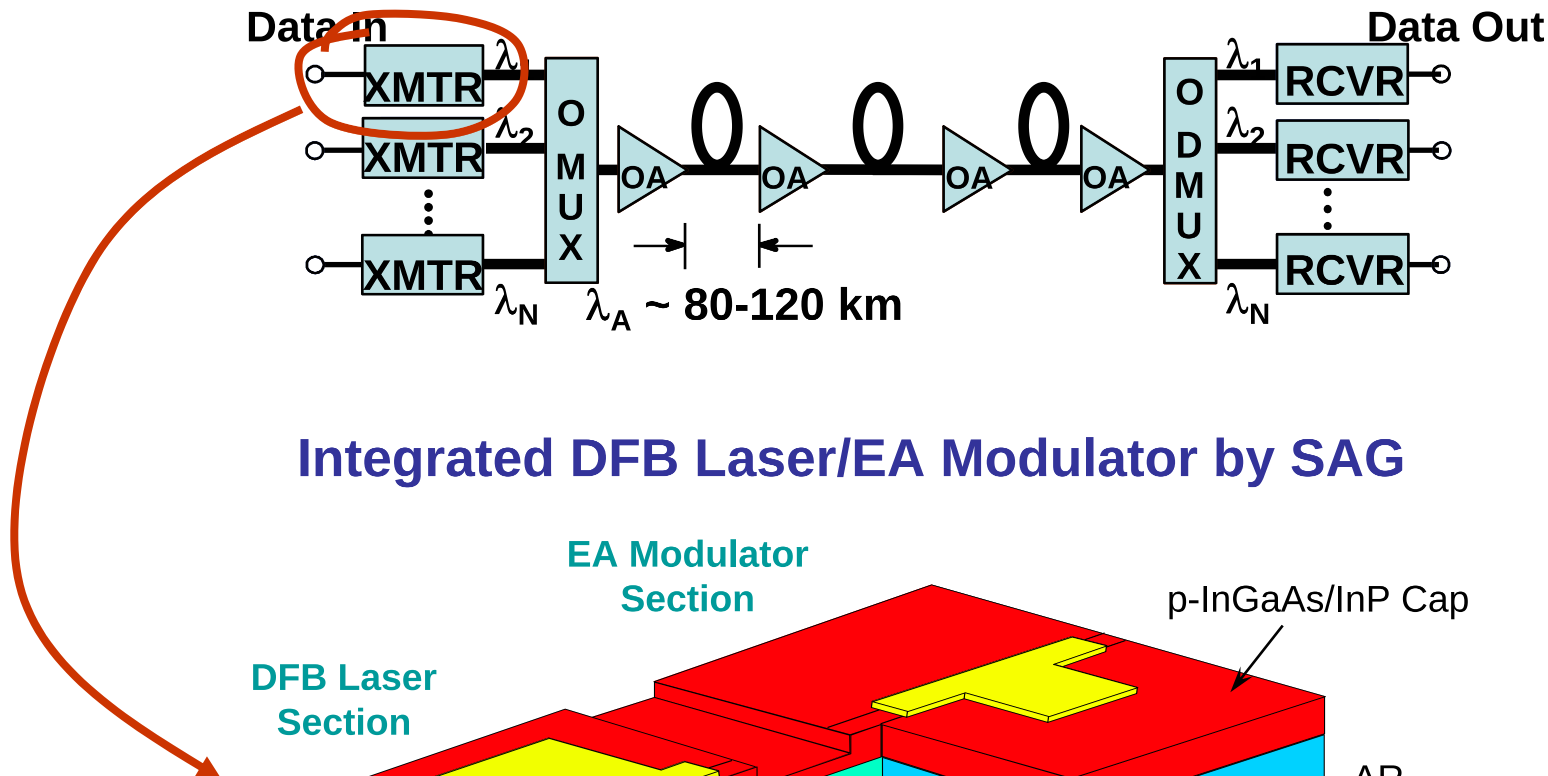
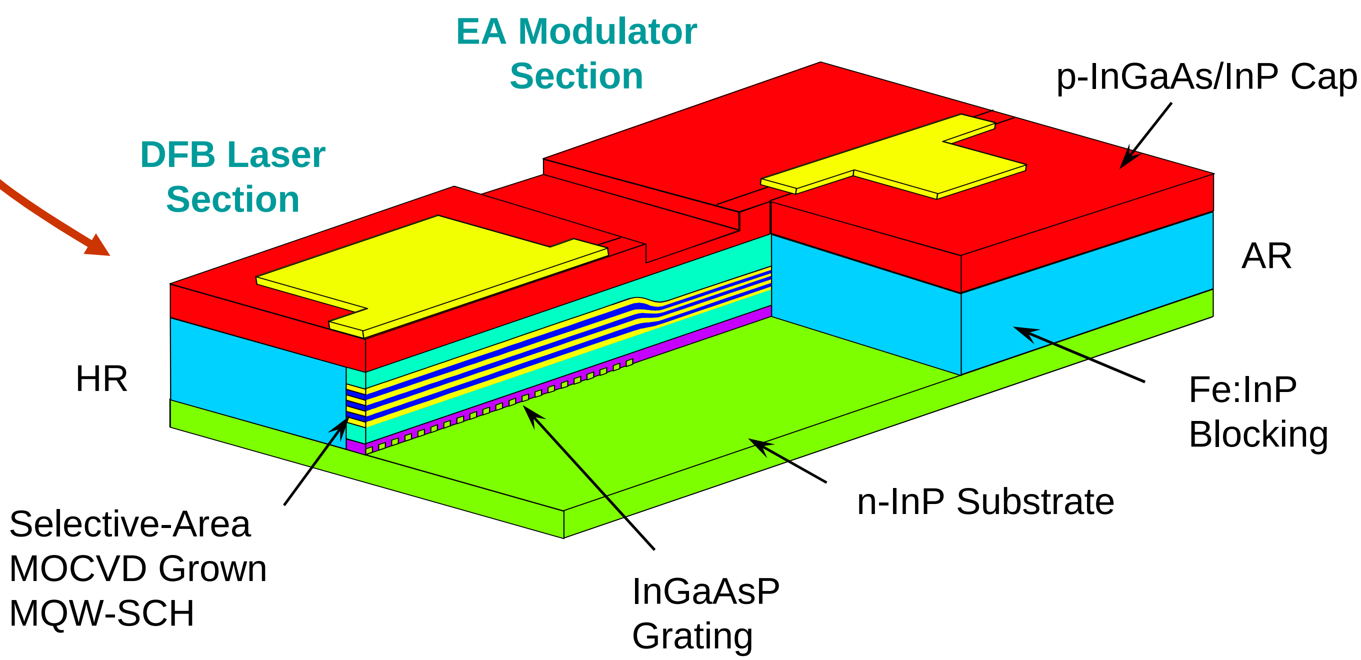
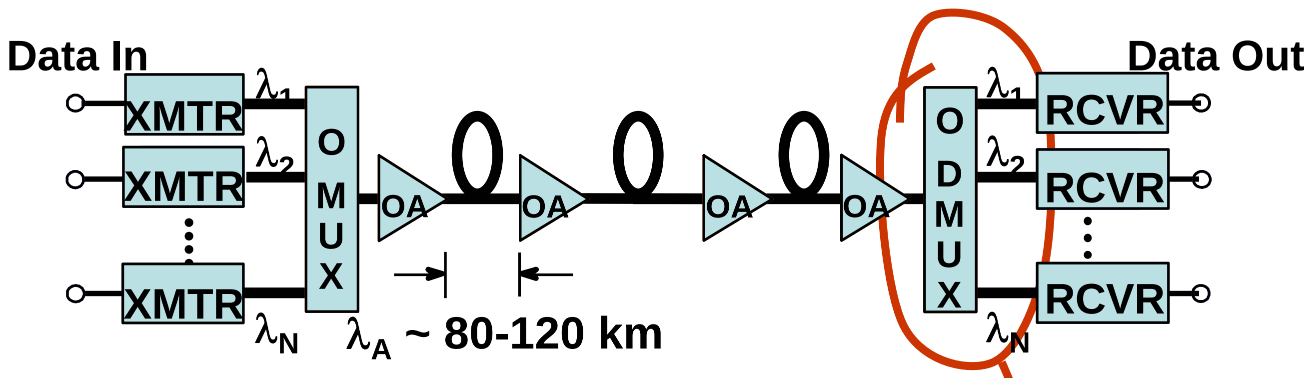
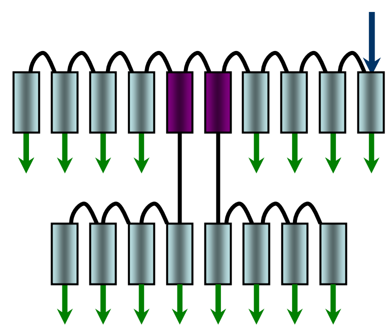


Integrated DFB Laser/EA Modulator by SAG



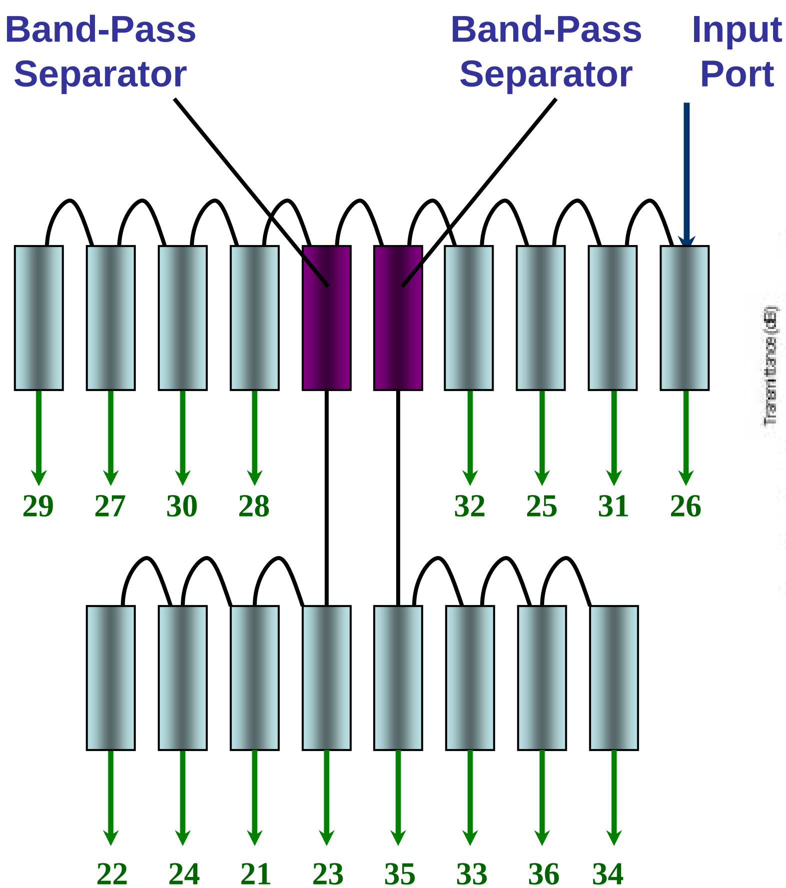


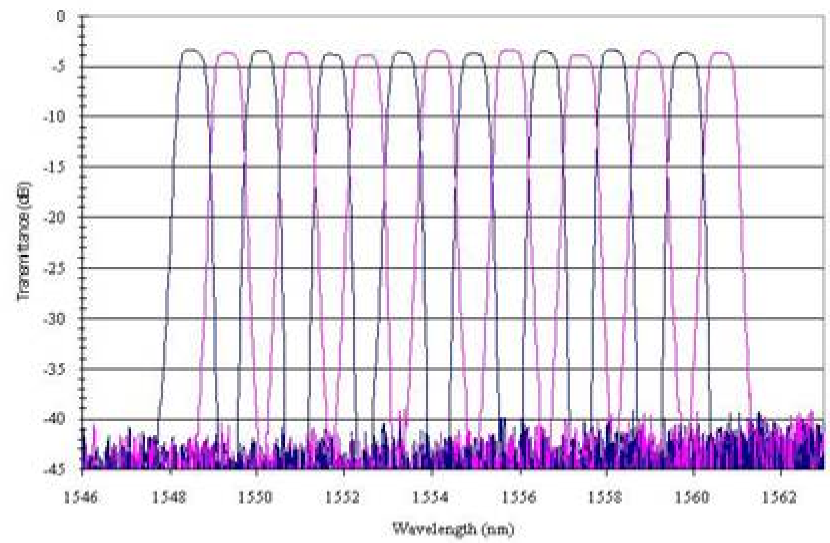
What about the receive demux side?



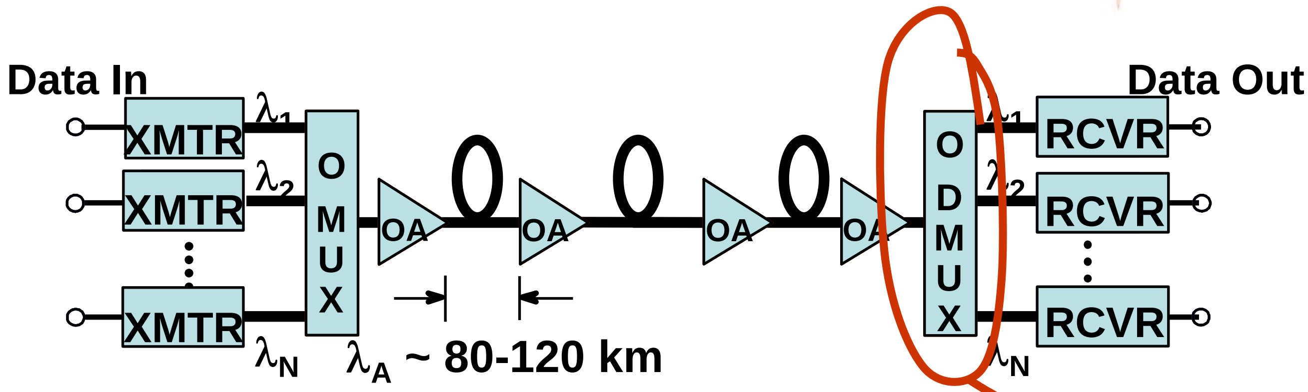
Discrete solutions: Cascaded Thin-Film Filters

Typical TFF Demux Configuration
Ex: 100 GHz 16-Channel

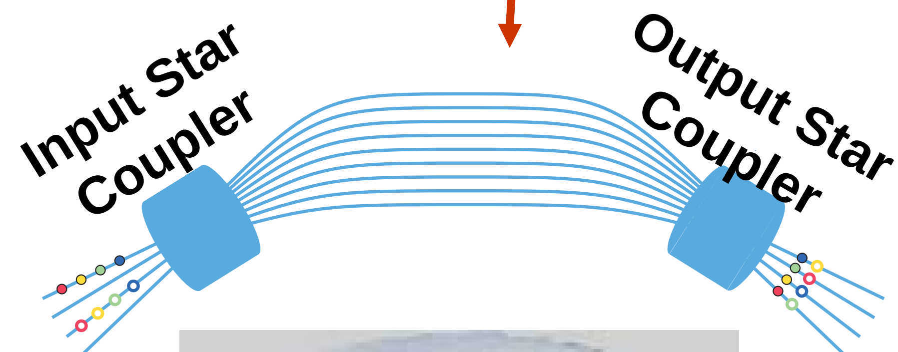




What about 160-channel?



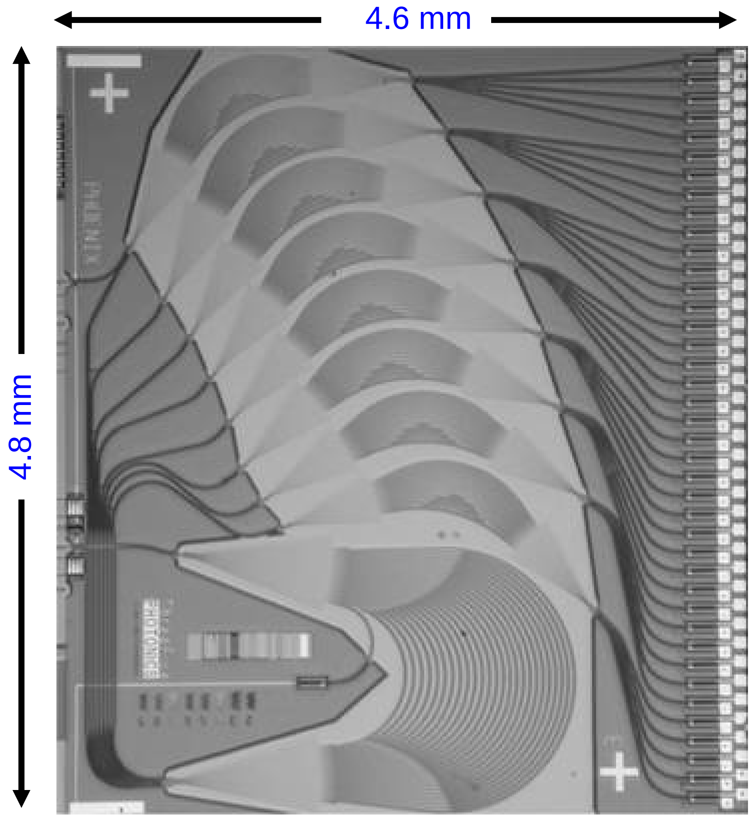
Si/SiO_2 Waveguide Grating Router:



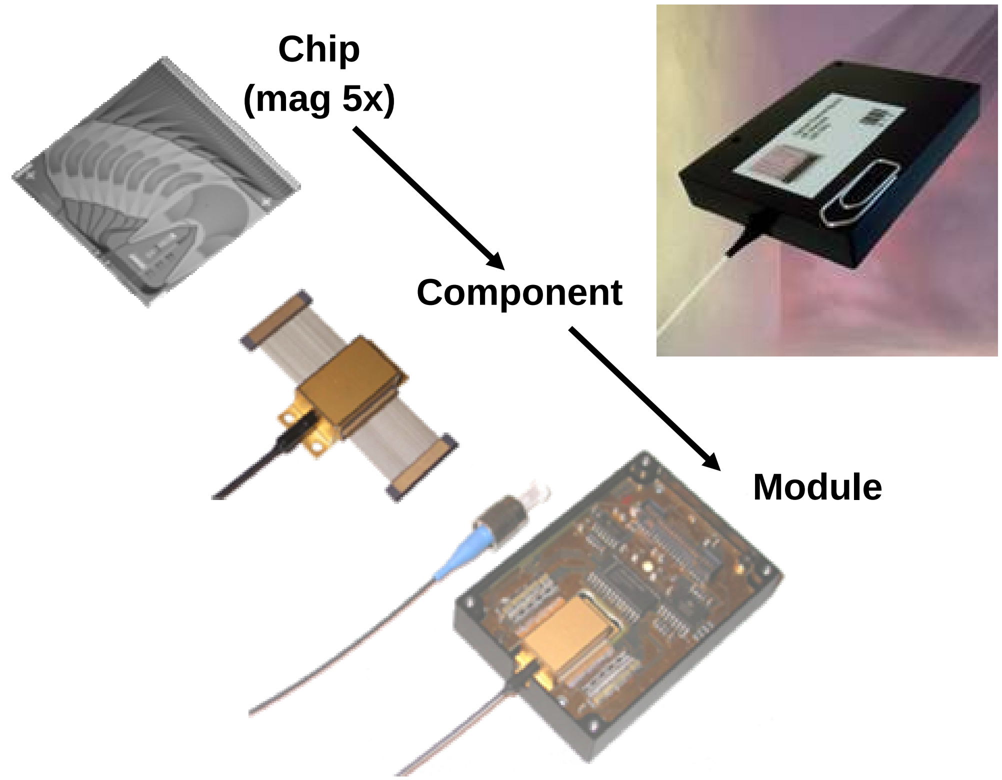
- Readily scalable to large channel count
- Wafer scale processing
- Stable, inexpensive optical interconnections

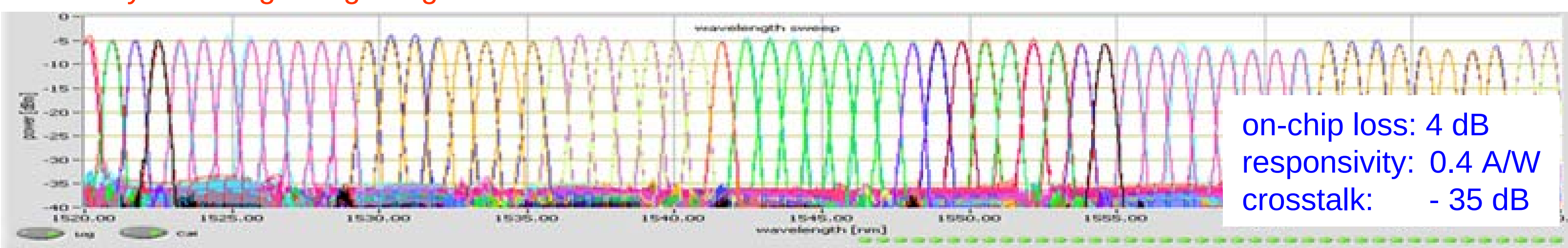
Today's technology for WDM integration:

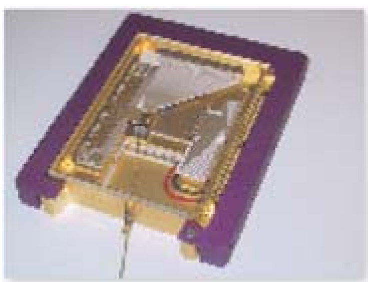
World's smallest integrated AWGs: 40 channels integrated



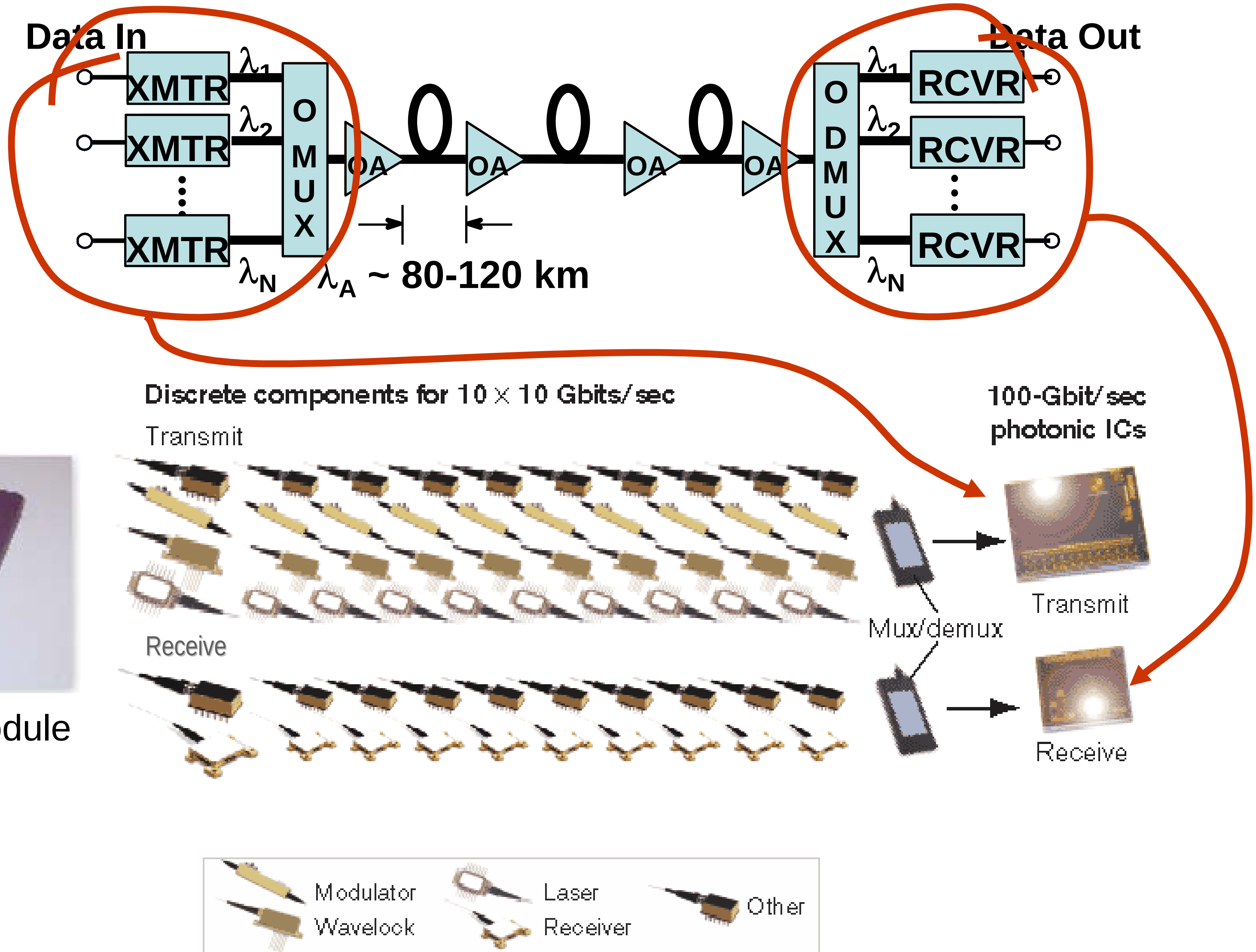
9 arrayed waveguide gratings+ 40 Photodetectors







Packaged Module



2005 WOCC – Newark April 22, 2005

But there's also some subtlety …

Two kinds of replacement technology…

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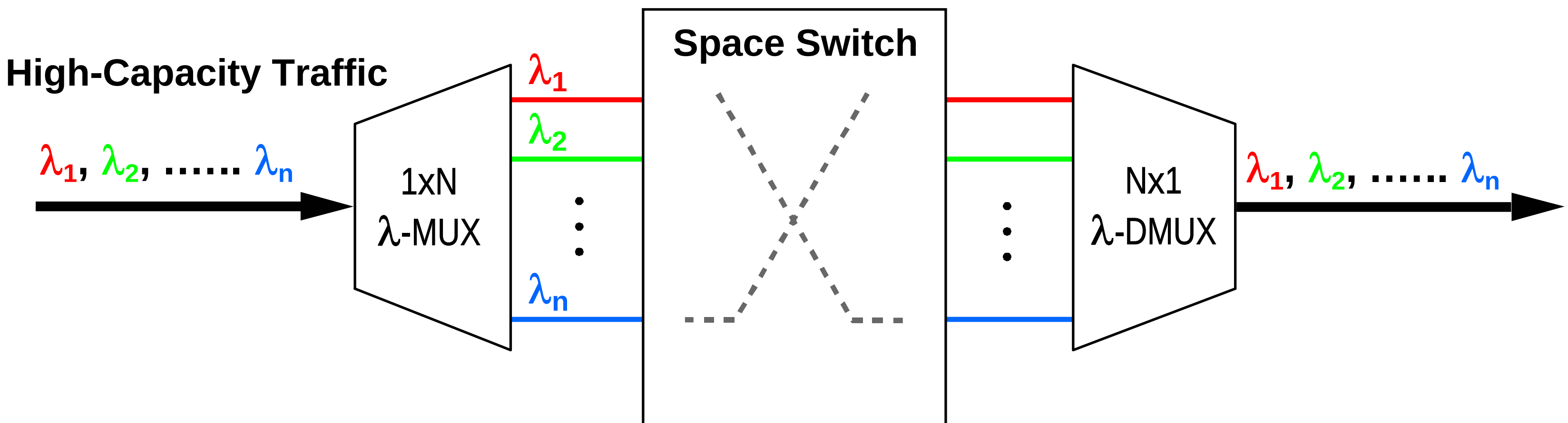
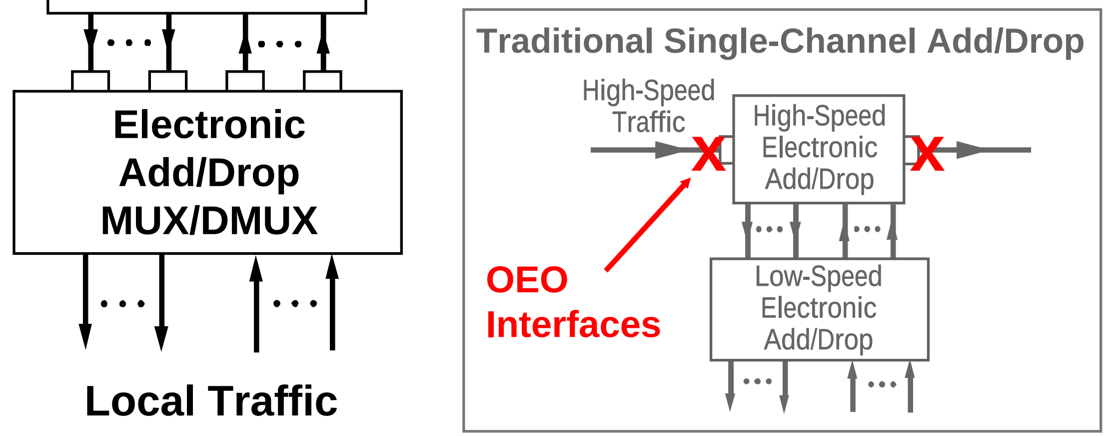
RECONFIGURABLE ACTIVE WDM ADD/DROP





- **Reduced cost dynamic provisioning at λ granularity without full OEO**

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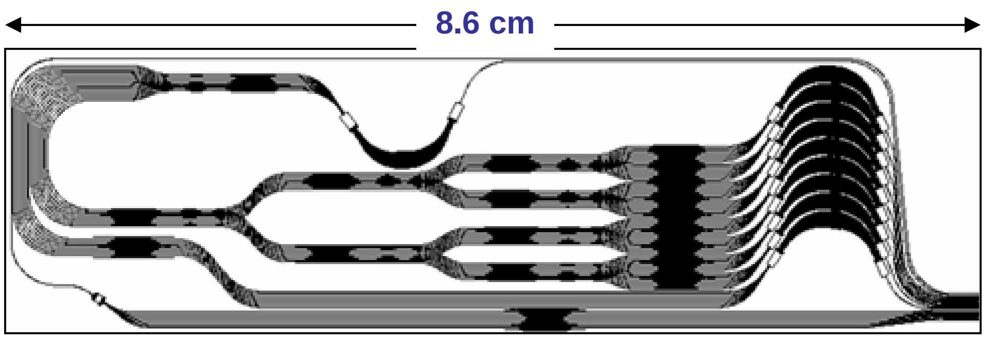
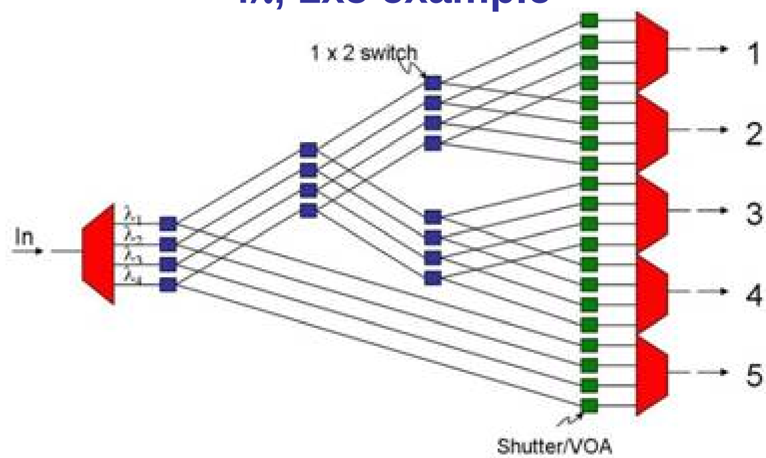
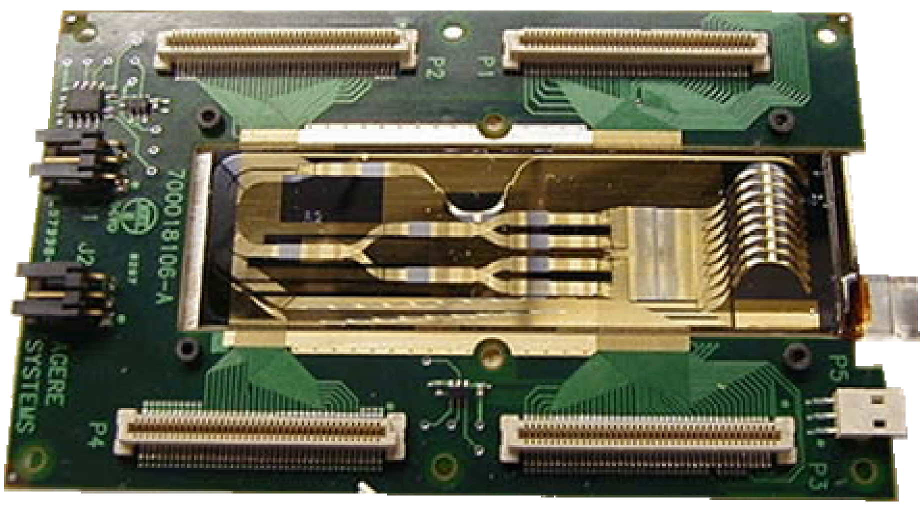
8-λ 1 × 9 Wavelength Selective Cross-connect

Doerr et al, Bell Labs



4λ, 1x5 example



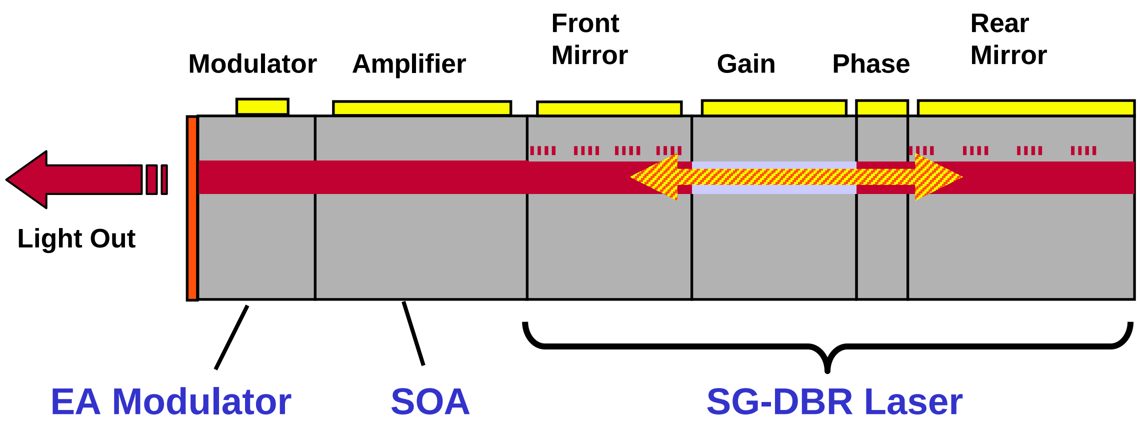


Features:

- 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**



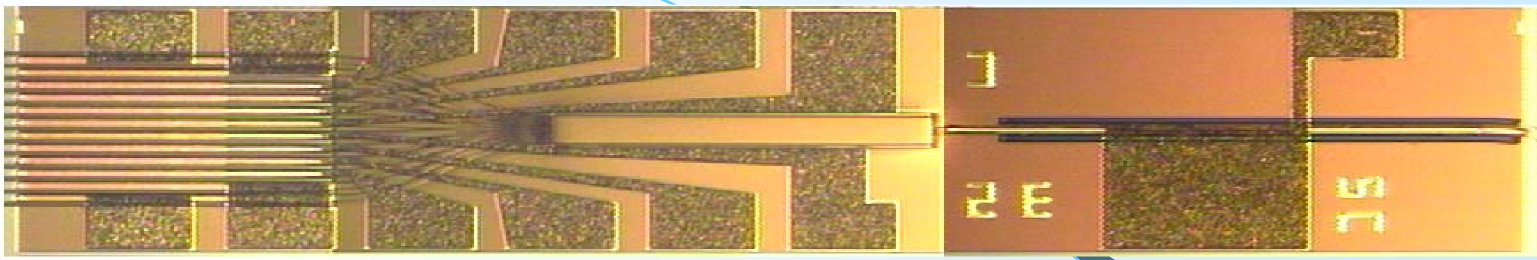
Advantages:

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

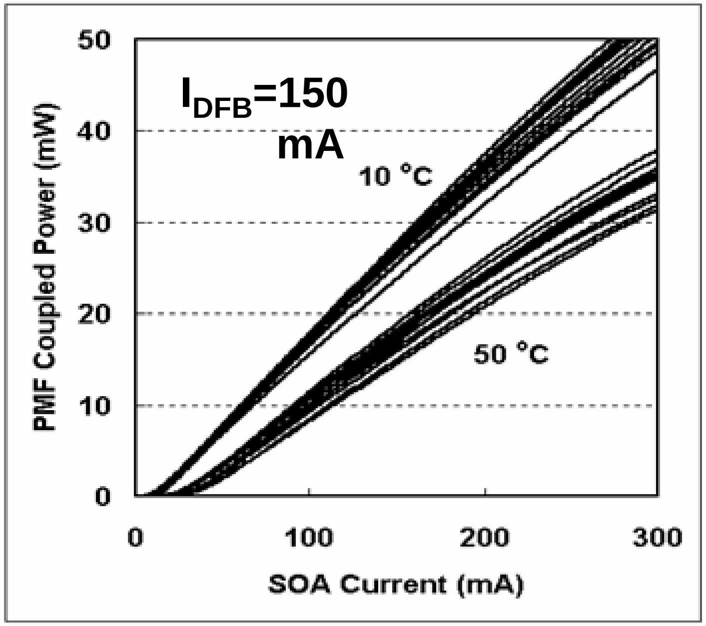
AGILITY

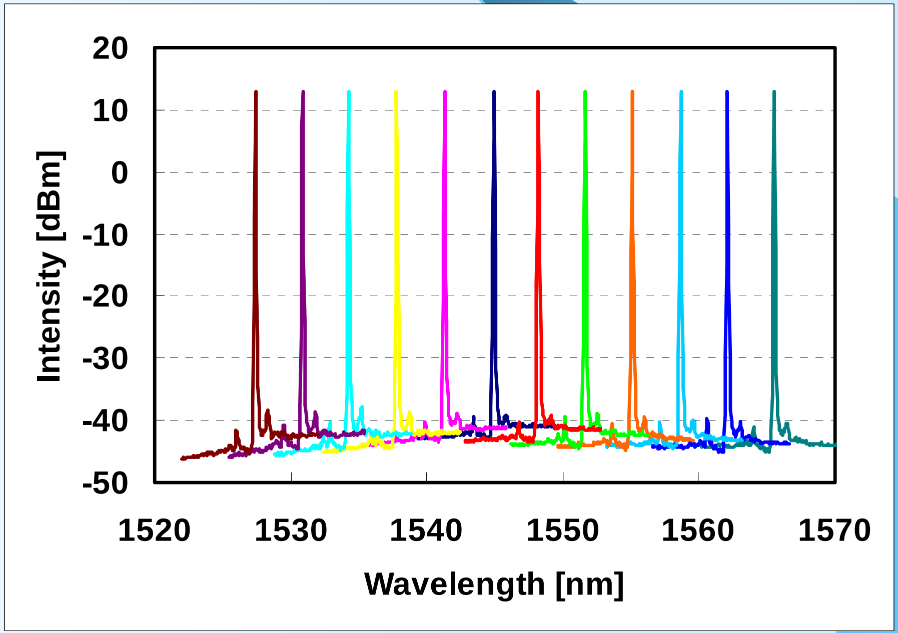
We can.

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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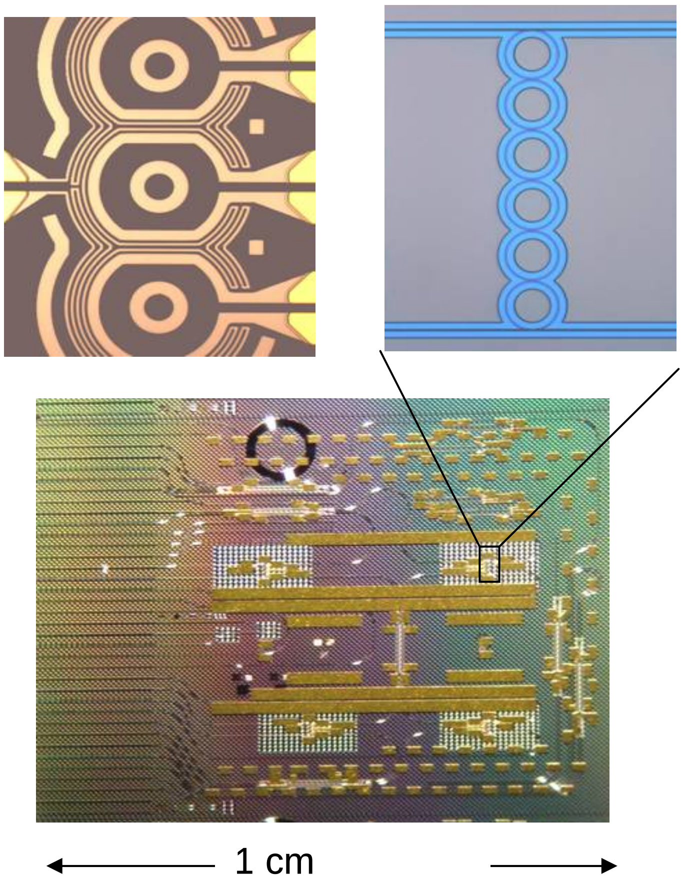
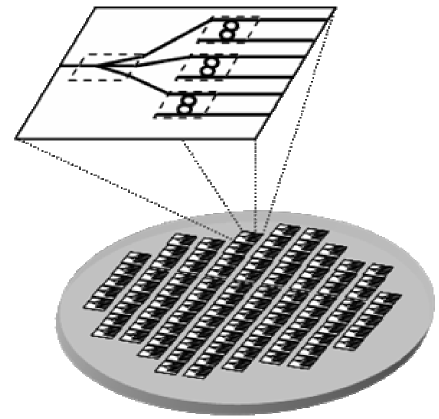
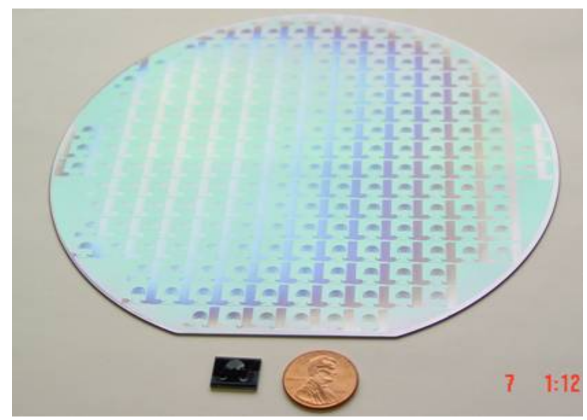




Little Optics



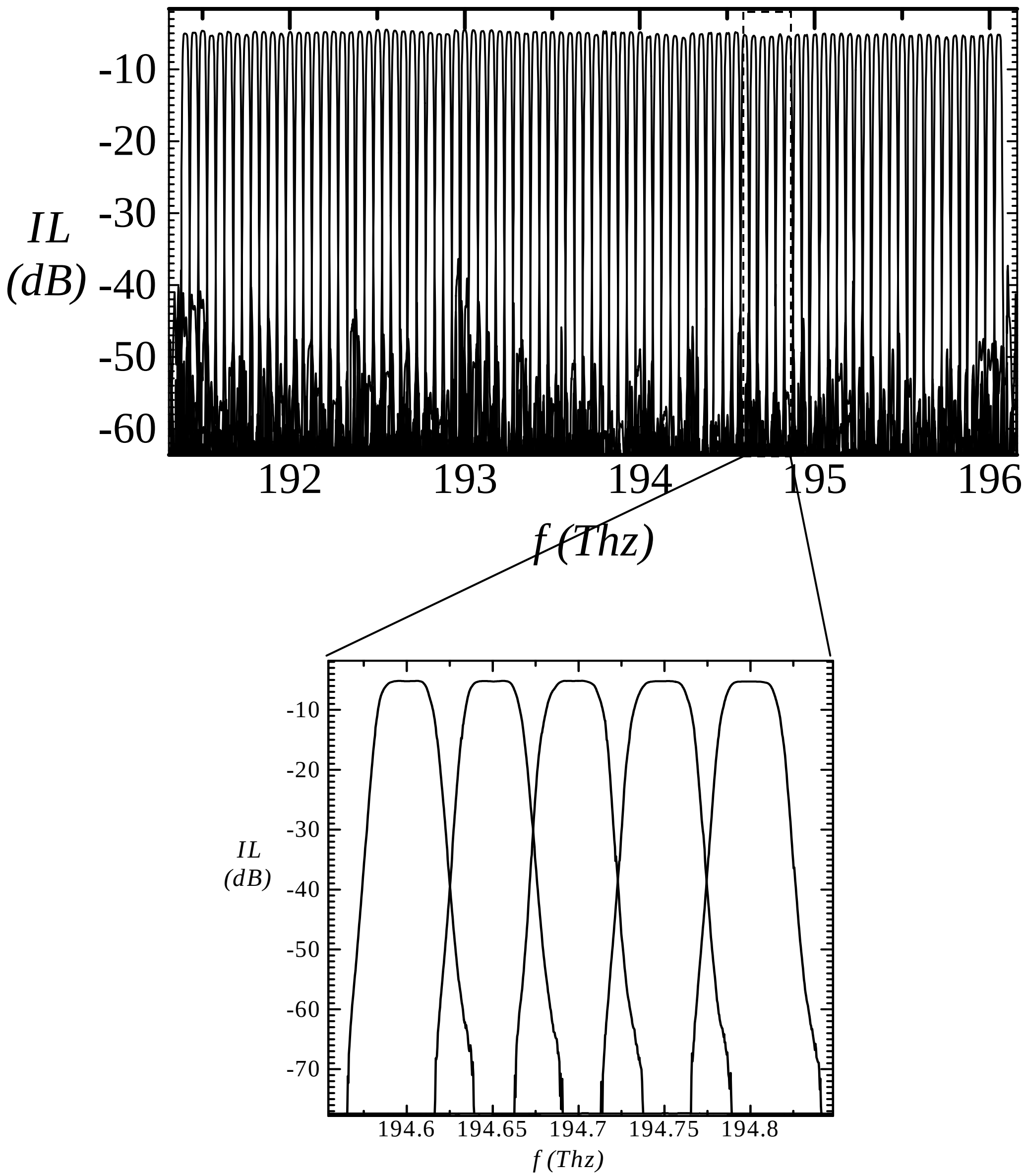
Dense Functionality on a Chip

(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)

High Performance & Functionality

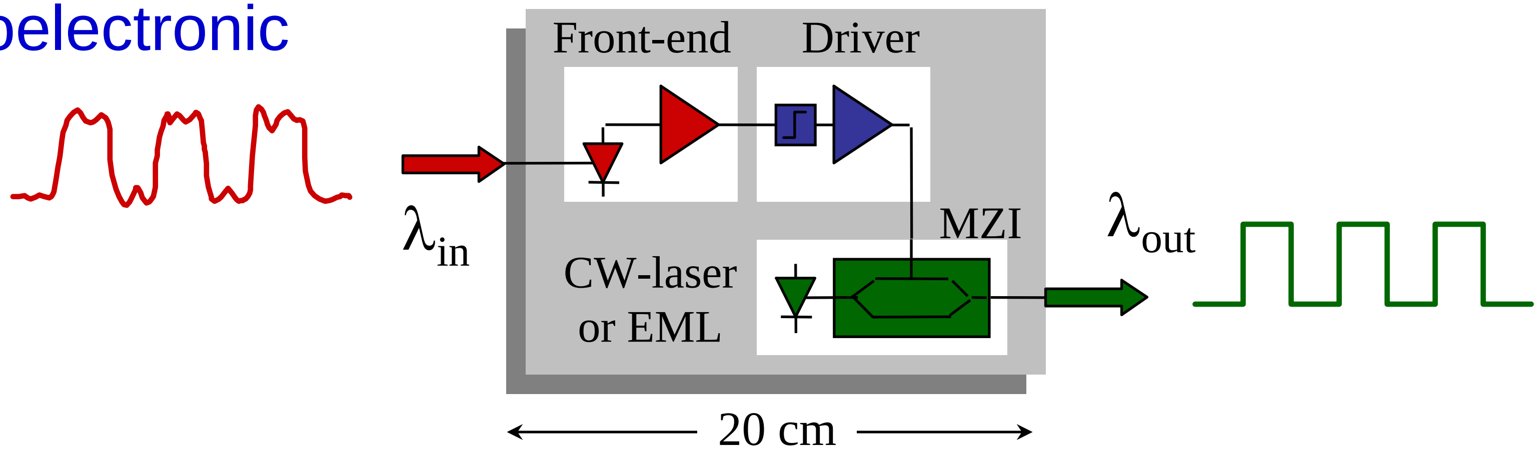


Channels	=	100
Avg IL	=	4.1 dB
Avg PDL	<	0.5 dB
Avg 1 dB BW	=	28 Ghz
Avg 3 dB BW	=	33.0 Ghz

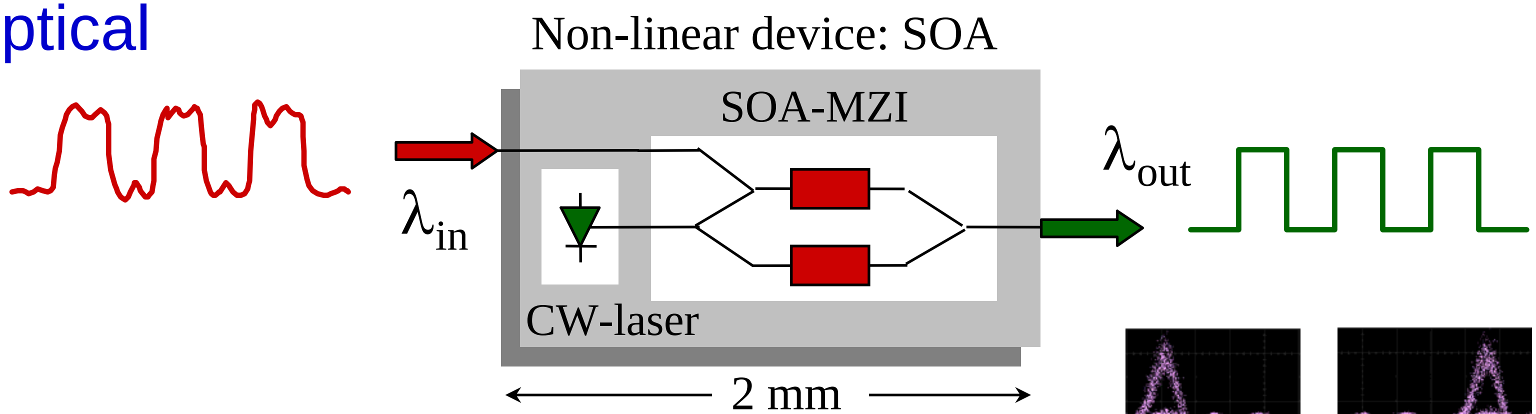
Full C-band (or C+L) Tunable Filters

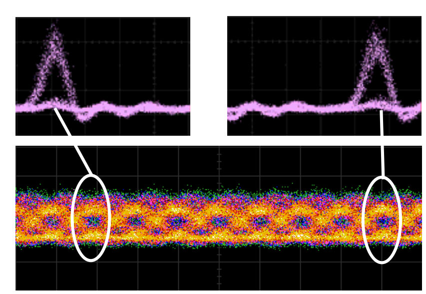
Optical regeneration

Optoelectronic



All-optical





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

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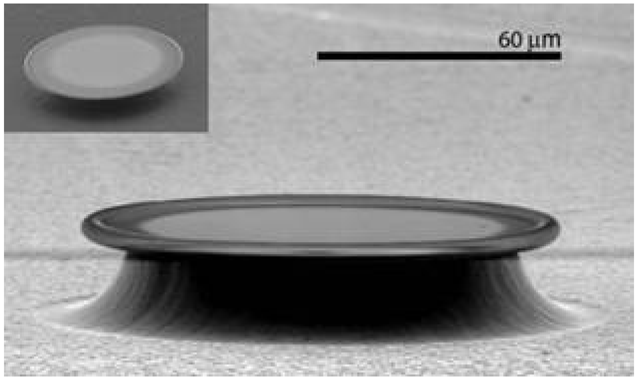
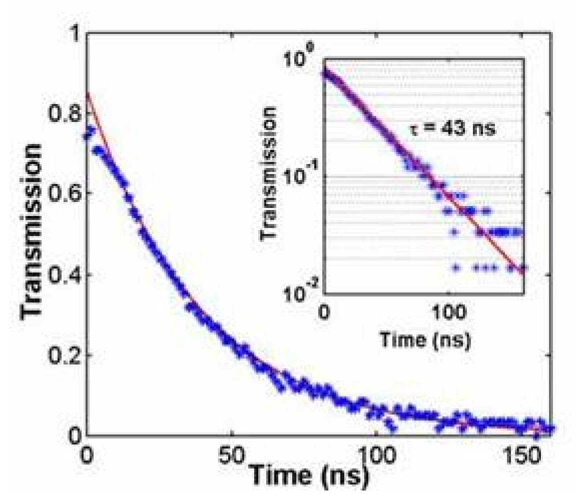
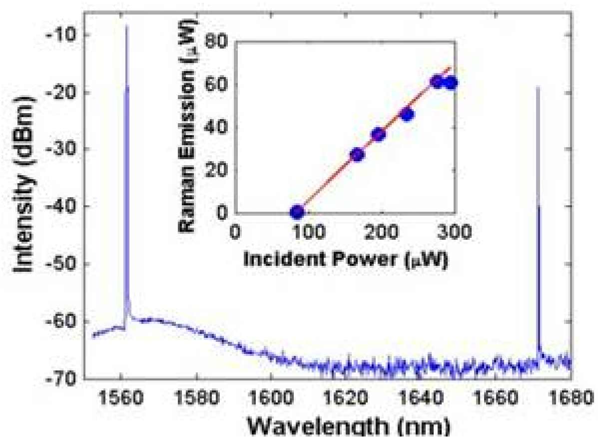
Resonant-Enhanced Functionality:

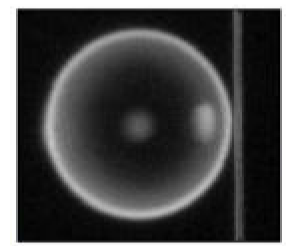
Vahala et al, Caltech





- **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!***

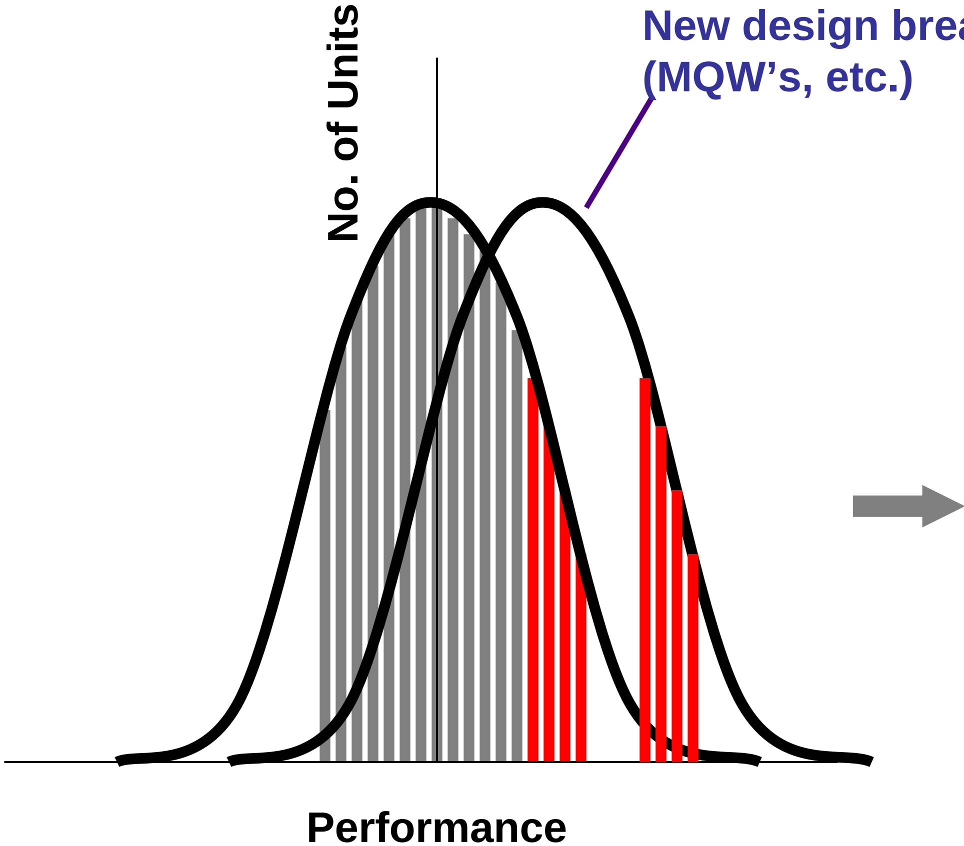




Single longitudinal mode Raman lasing in a 40-µm diameter microsphere, exhibiting 16% pump conversion. Inset: η_d = 36%.

Think analog IC's & microwave mixing techniques

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 …*

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:

- 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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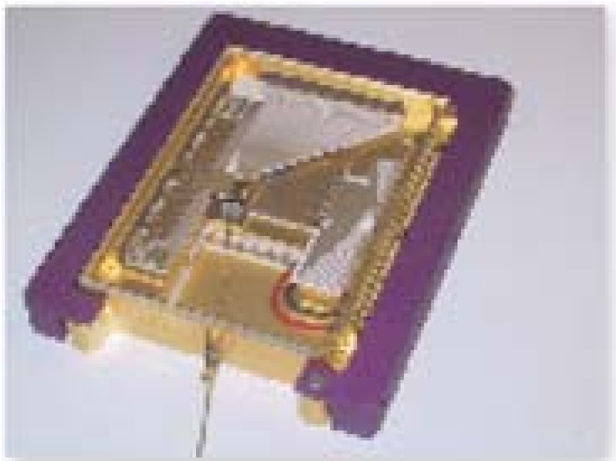
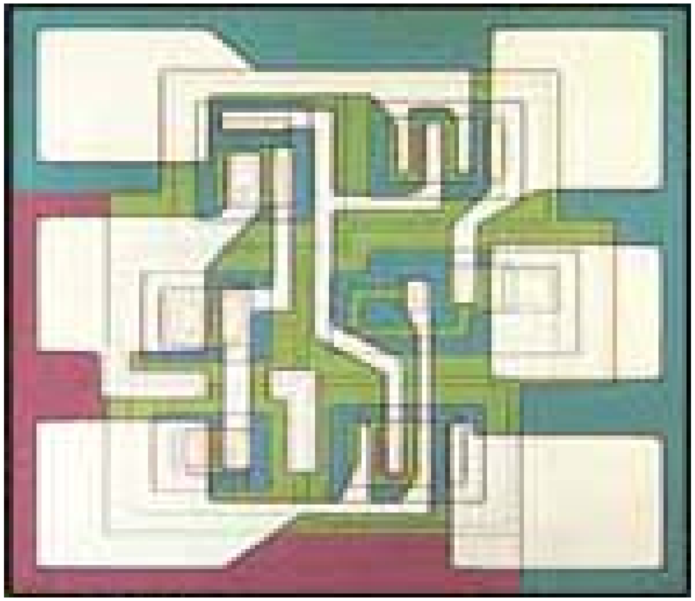
For the naysayers …..

infinera





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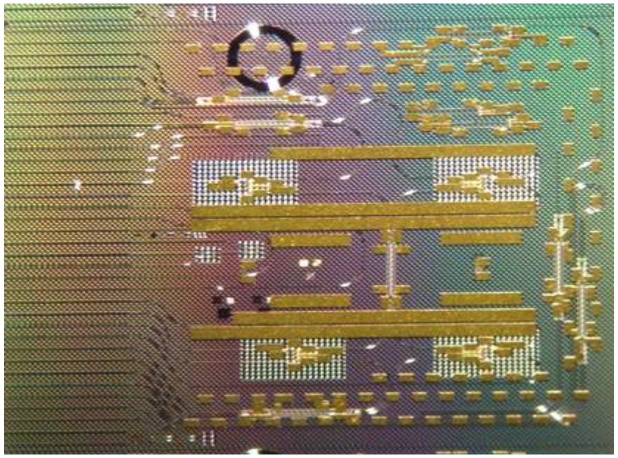

Already exceeding complexity of 1st generation analog IC's!