Optical Networks - A View to the Future
Sarnoff Symposium
Princeton, New Jersey
March 31, 2009

Rod Alferness
Chief Scientist, Bell Labs
Alcatel-Lucent
October 31, 2008

A Worldwide Web of Optical Experts - My Thanks for Input!

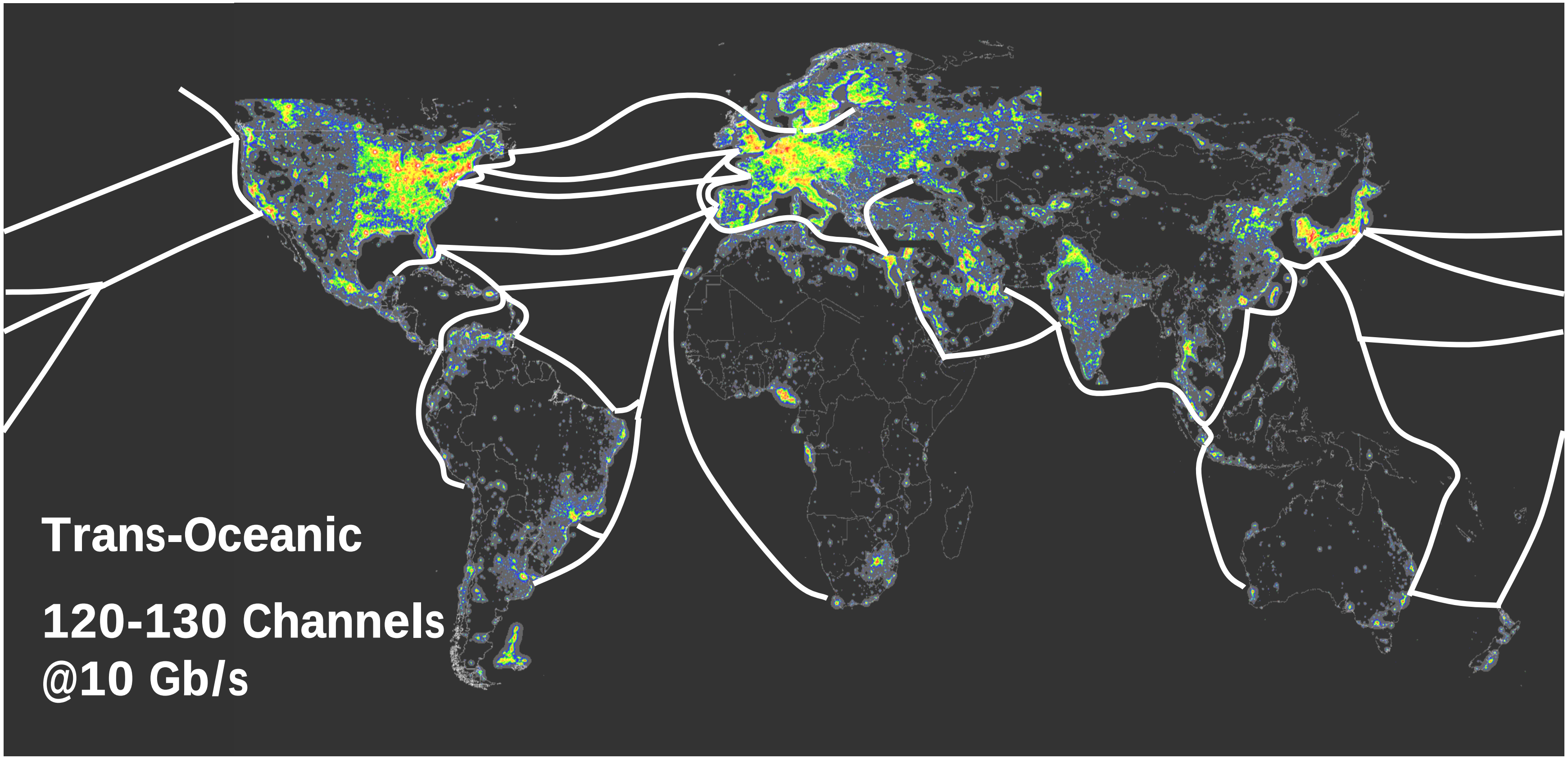
Neal Bergano
Pietro Bernasconi
Sebastien Bigo
Dan Blumenthal
Y. K. Chen
Andy Chraplyvy
Larry Coldren
Chris Doerr
Rene Essiambre
Olivier Gautheron
Cary Gunn
JDSU
Herwig Kogelnik

Steve Korotky
Ton Koonen
David Nielsen
Adel Saleh
Iraj Saniee
Chandrasekhar Sethumadhavan
Kenichi Sato
Meint Smit
Bob Tkach
Rod Tucker
David Welch
Alan Willner
Peter Winzer

Where Are We Today - Undersea, Long Haul, Metro and Access

Undersea Networks

Flattening the World and Enabling a Global Community!

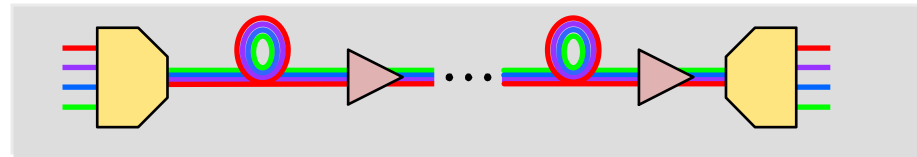


Adapted from Undersea Cable, KDD-SCS, 2000 and Night Sky Artificial Light, Cinzano, Falchi, and Elvidge, MN_RAS, 2001.

Optical Transport Networking Evolution: A View from the ’90s

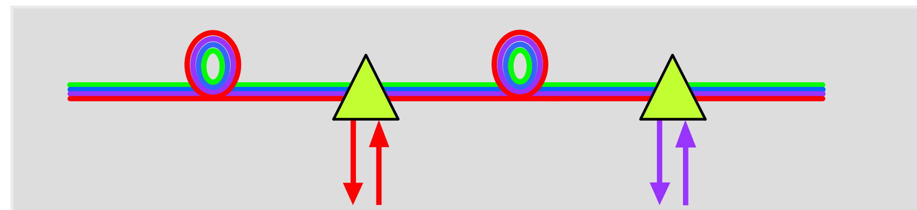
WDM/Point-to-Point Transport

- High Capacity Transmission



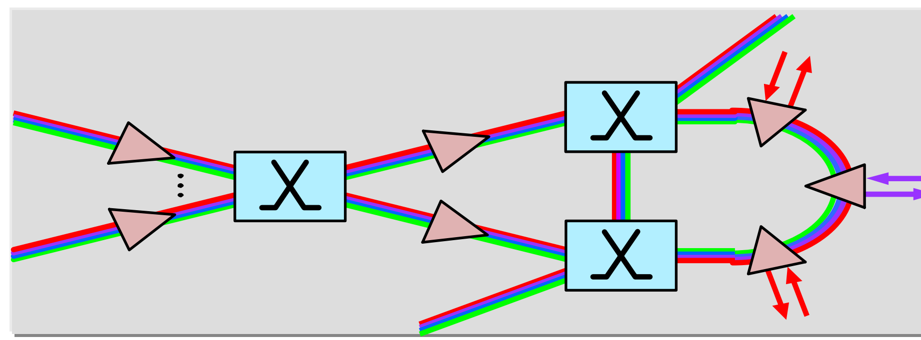
Fixed WDM/Multipoint Network

- Fixed Sharing Between Multiple Nodes
- Passive Access of Wavelength Channels



Photonic XC and WADM
Reconfigured WDM/Multipoint Network

- Automated Connection Provisioning
- Flexible Adjustment of Bandwidth
- Network Self-Healing/Restoration

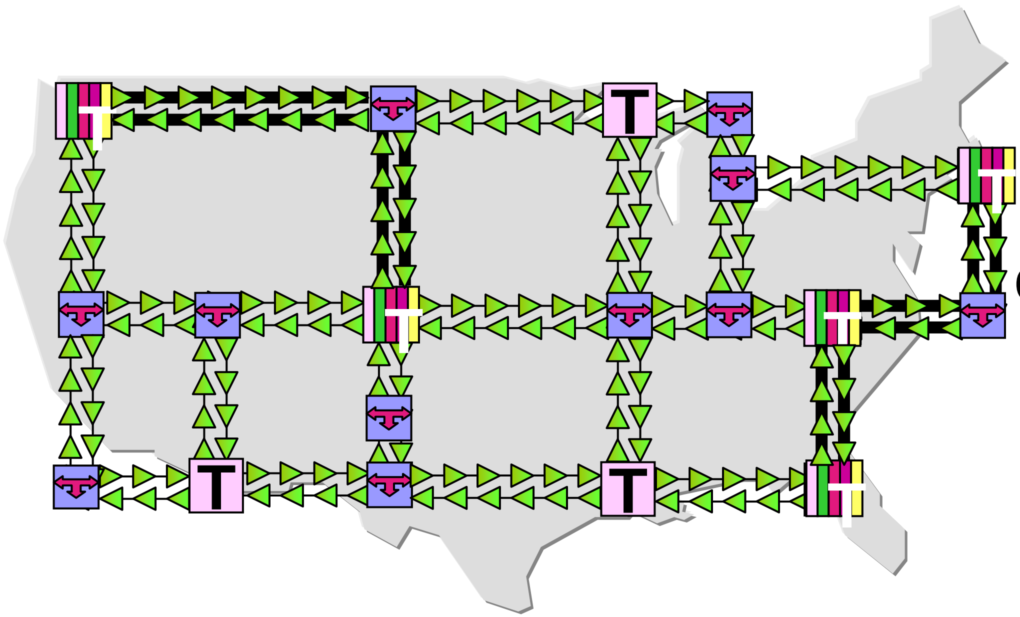


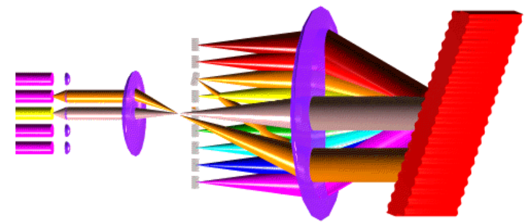
A Reality Today!

Fiber Amplifier
Wavelength Multiplexer/Demultiplexer
Wavelength Add/Drop (ROADM)
Wavelength Cross-Connect

Mesh and Ring Reconfigurable WDM Networks

Leverage OA's and ROADM/OXC's for Reduced Network Cost





Commercial Long Haul Systems:

~ 1-5 Tb/s (~100x that 1998!)

~ 80 Wavelengths@40 Gb/s

ROADM (Reconfigurable Optical Add/Drop Multiplexer)

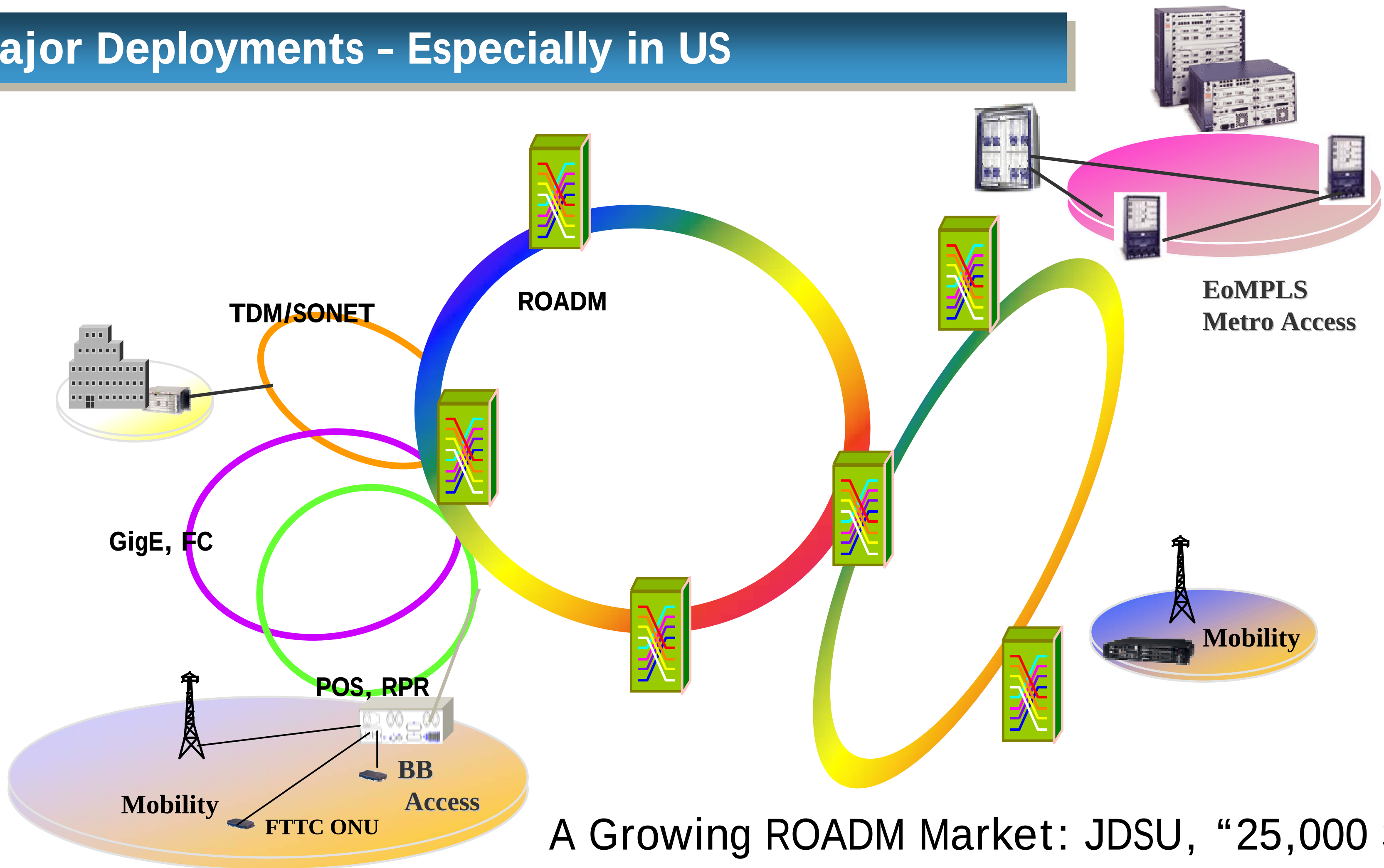
T Terminal Equipment

Right Architecture When:

- Network Requires the Connectivity and Capacity
- Node to Node Demands Justify Wavelength Express- Groom at Edge
- ROADM $ Competitive with Terminal plus High Capacity Elect ADM

ROADM-Based Metro Networks

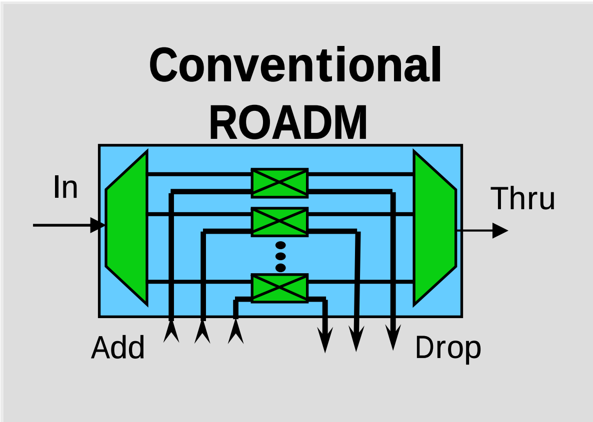
Major Deployments – Especially in US

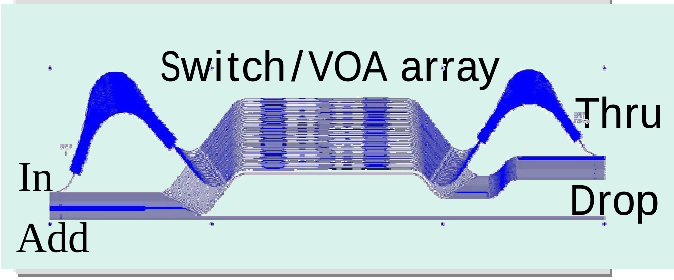


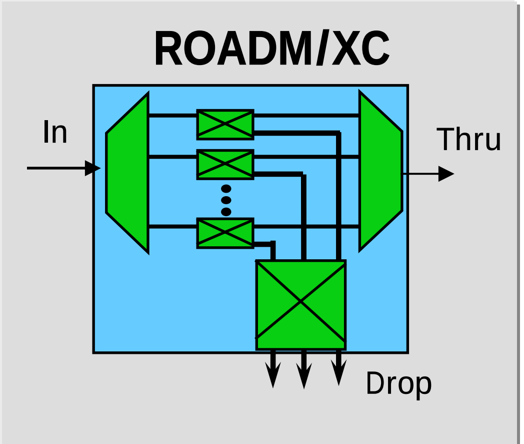
A Growing ROADM Market: JDSU, “25,000 Sold,
Courtesy JDSU

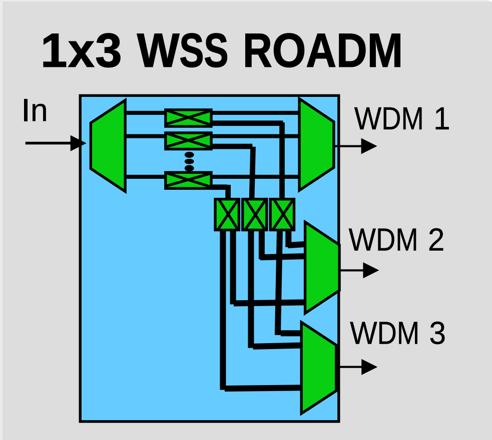
ROADM Evolution

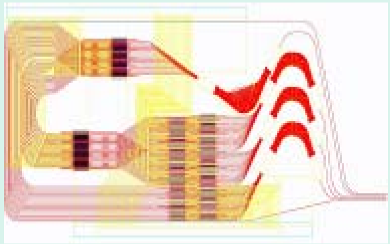
Enhances Functionality to Improve Remote Configuration and Reduce Operation Costs.







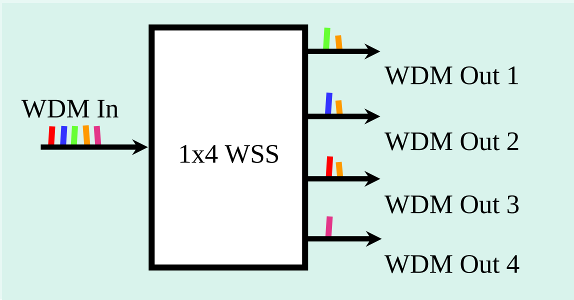




Higher Capacity, More Flexible Connectivity, Smaller Footprint and Lower Cost

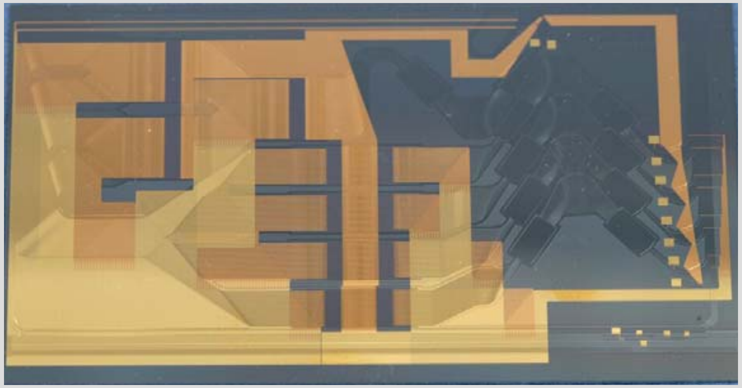
1xN Wavelength Selective Switch (WSS)- ROADM Building Module→ Scalable to NxN Cross-Connect

▪ 1xk WSS Function:



1x4

40λ, 1x4 WSS PLC:

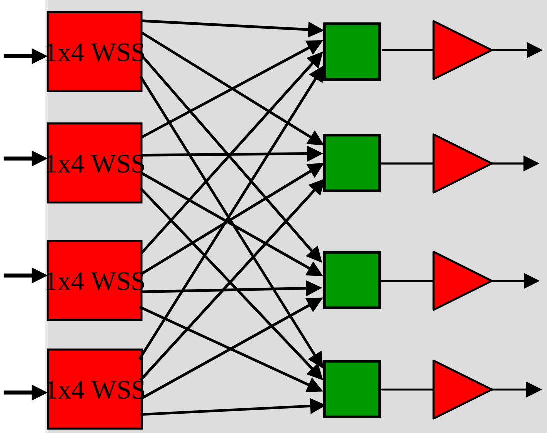


35x70mm

▪ Large Scale Integration PLC

- 40 wave flat-top AWGs (5 elements)
- 1x2 switching stages (120 elements)
- VOA arrays (160 elements)
- 2 levels of metal interconnect

Wavelength cross-connect:



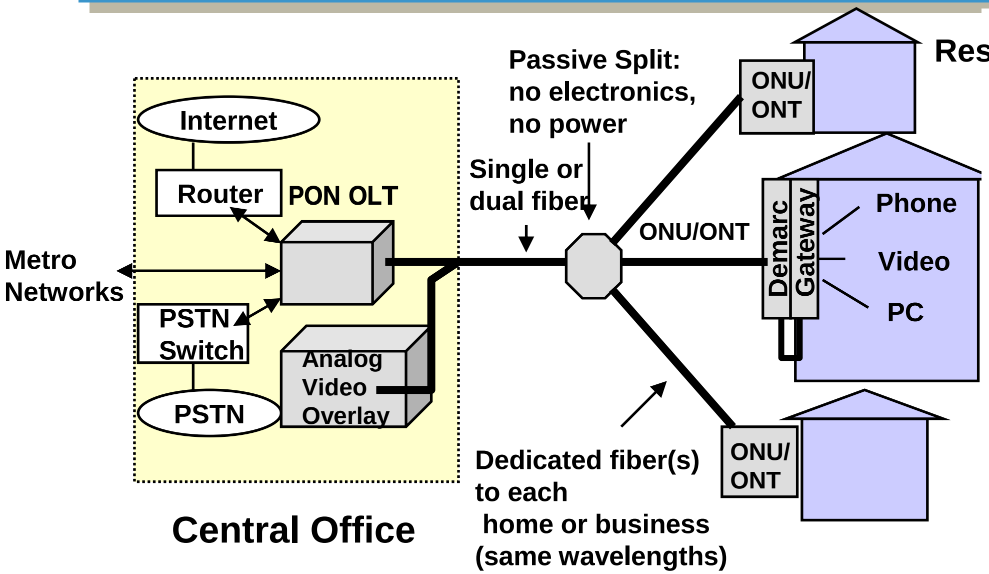
▪ PLC Advantages:

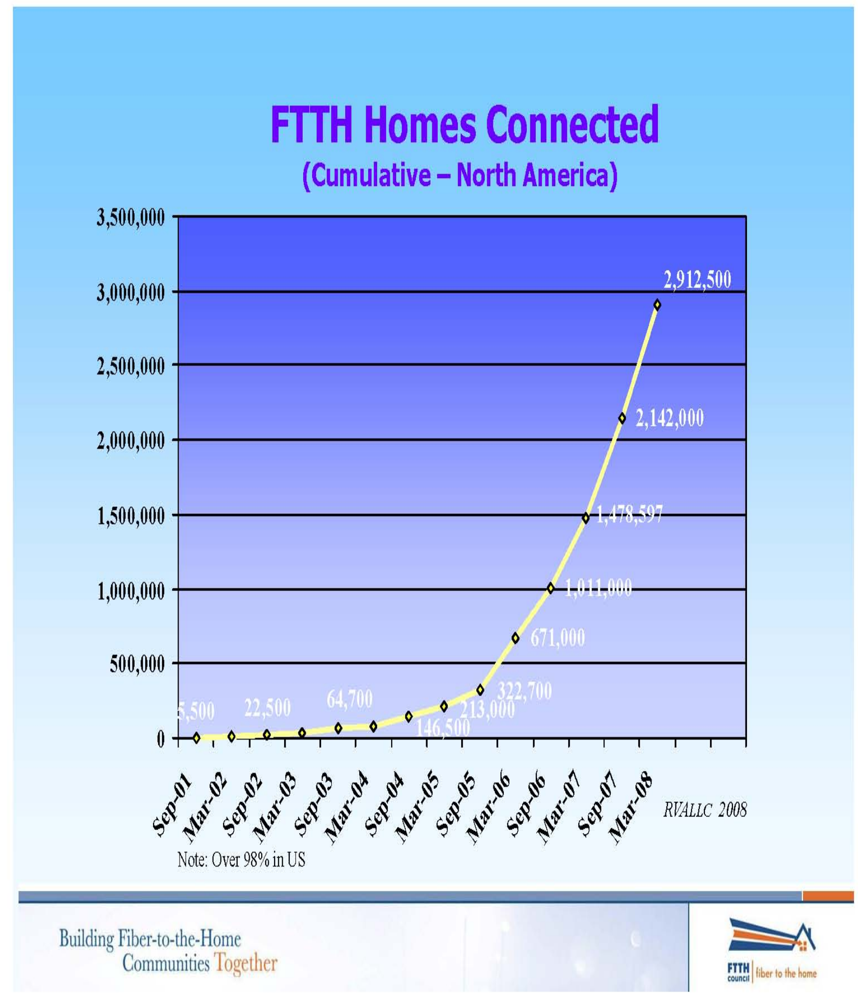
- low cost non-hermetic packaging
- hitless switching
- narrowcast, multicast and broadcast flexibility

Mark Earnshaw

Fiber Expanding into Access

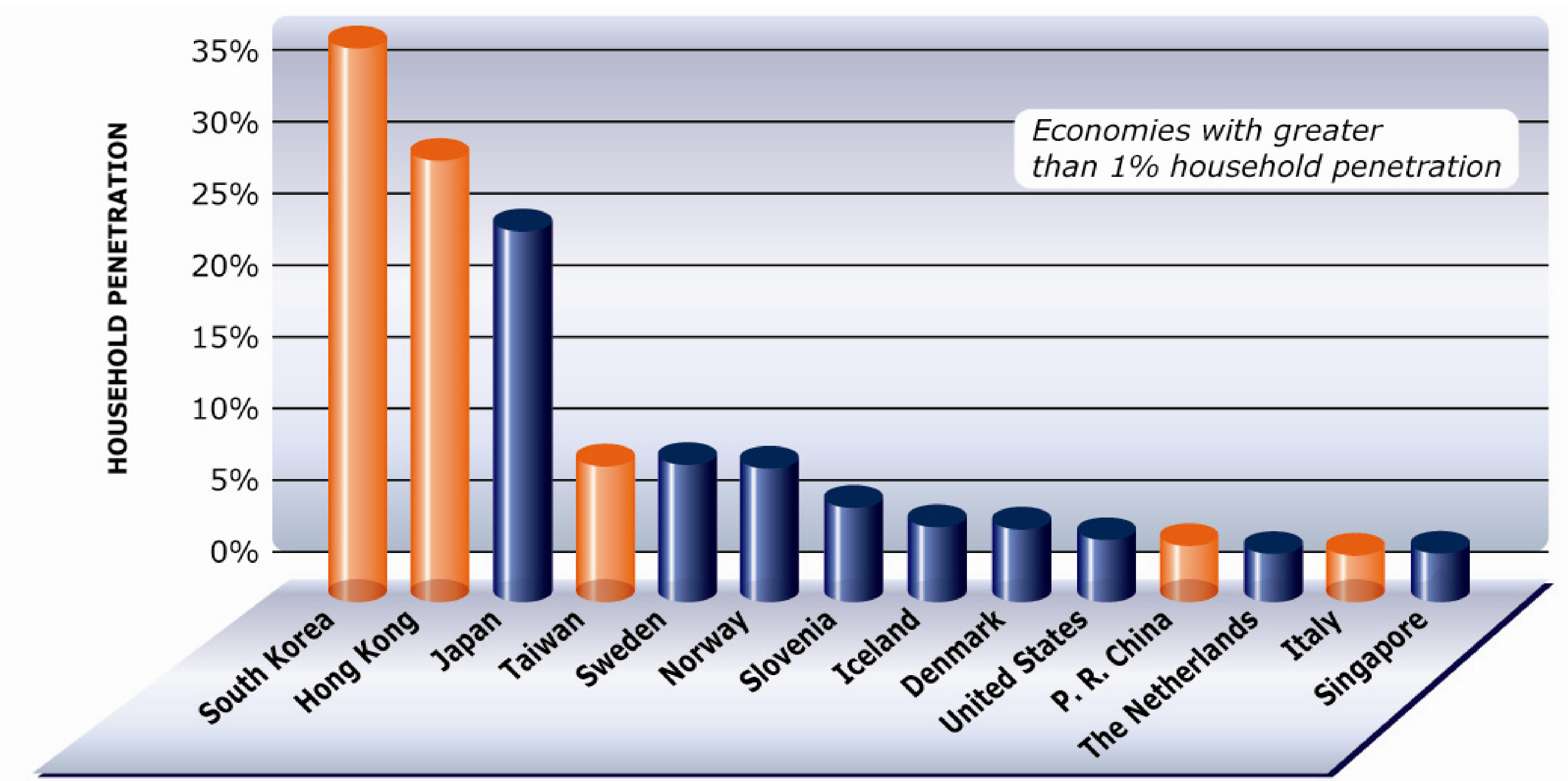
Broadband to business, homes, and base stations





Multi-faceted video is driving network demand!

Economies with the Highest Penetration of Fiber-to-the-Home/Building+LAN



Mid-Year 2008 Ranking
Source: Fiber-to-the-Home Council
Jul 08

Economies where majority architecture is **Fiber-to-the-Home**

Economies where majority architecture is **Fiber-to-the-Building+LAN**

What Will Drive Optical Networks of the Future

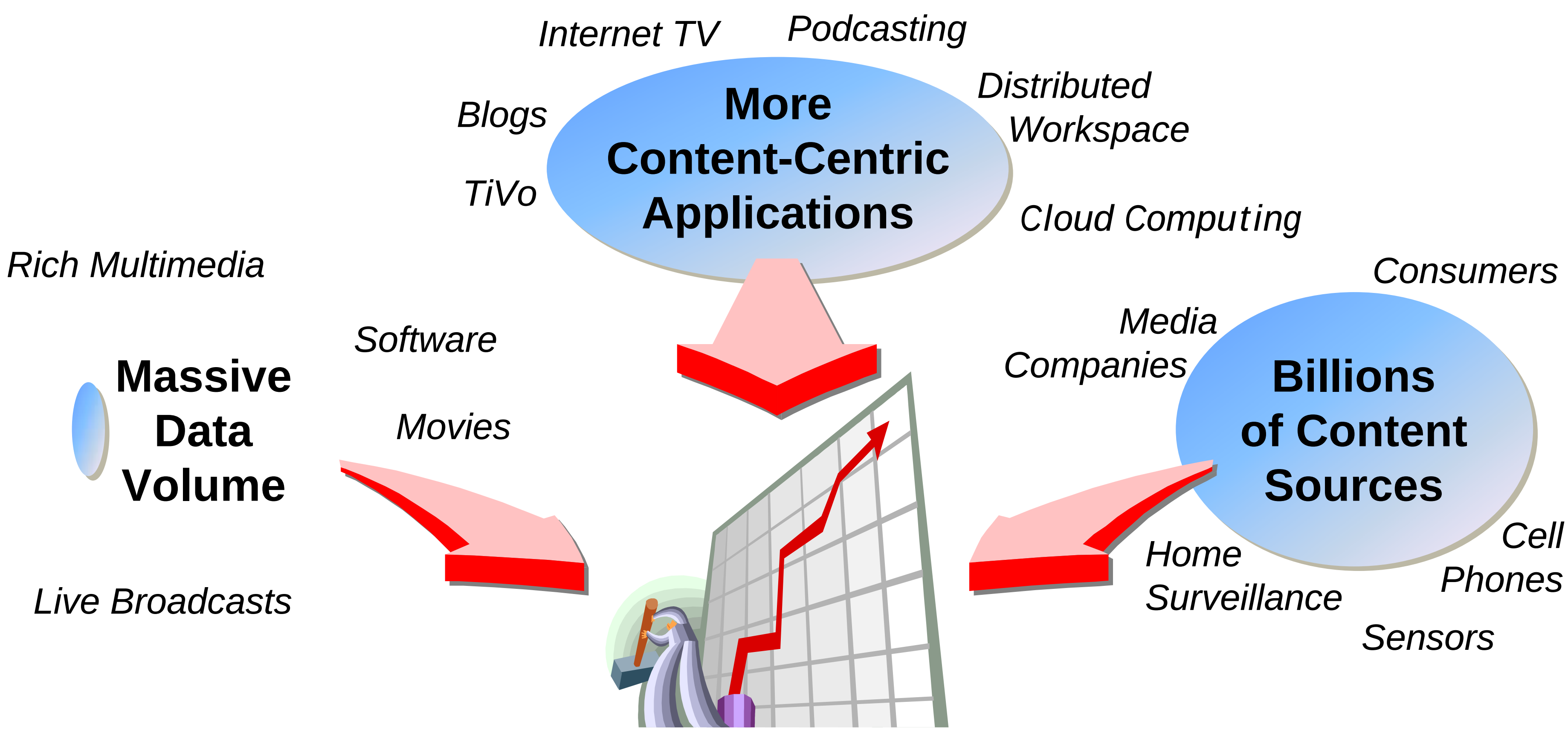
Current Environment

Some Shaping Forces

- **We Have "Flattened the World"**
  - People and Multi-Nationals Require Even More "Connection"
  - Growing Global "Digital" Population- "Reaching the Next Billion"
  - Growing Global Optics Research Community to Address Challenges
- **Energy and Carbon Footprint will Drive Future Network Architecture and Technology Decisions**
- **Our Industry is Very Different from 1998**
  - No "Seed Corn" from Monopoly and PTT Research Labs
  - Horizontal Industry Complicates Component Investment
  - "Over the Top" Companies Capturing Value of "The Network"

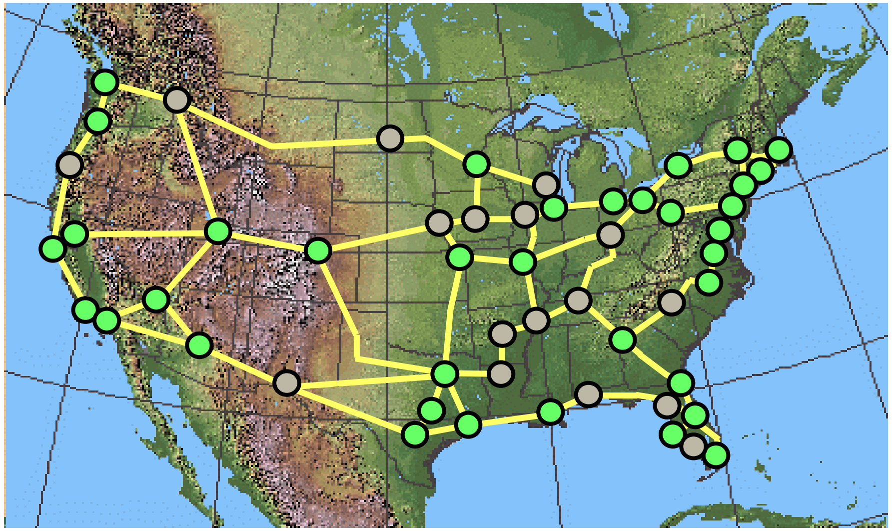
Powerful Forces Continue to Drive Capacity Demand Growth

... And it will become even more challenging.



... New Invention will be Essential to Meet the Demand!

Contemporary Backbone Network



- **Traffic**
  - **~16 PB/day (2007)**
- **Growth Rate**
  - **40-60% CAGR**

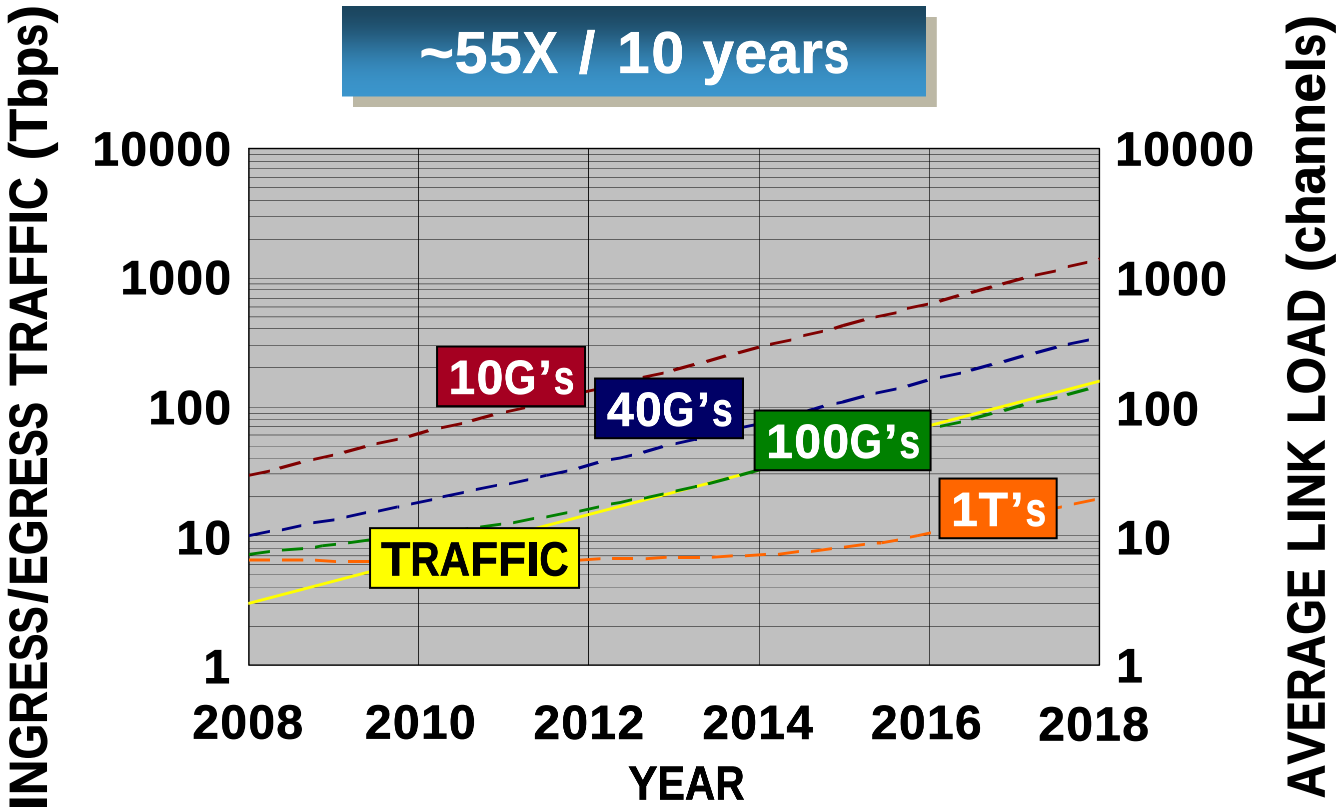
    (~30-110X in 10 years)

Source: Stankey, AT&T Analyst Conference, 2007.

Network Traffic and Link Loads

Scenario: 3 Tbps YE 2008 + 50% CAGR (4X/3.5year)

~55X / 10 years



2018: Terabit/sec Wavelengths?

Courtesy: Steve Korotky

"The Network" Going Forward

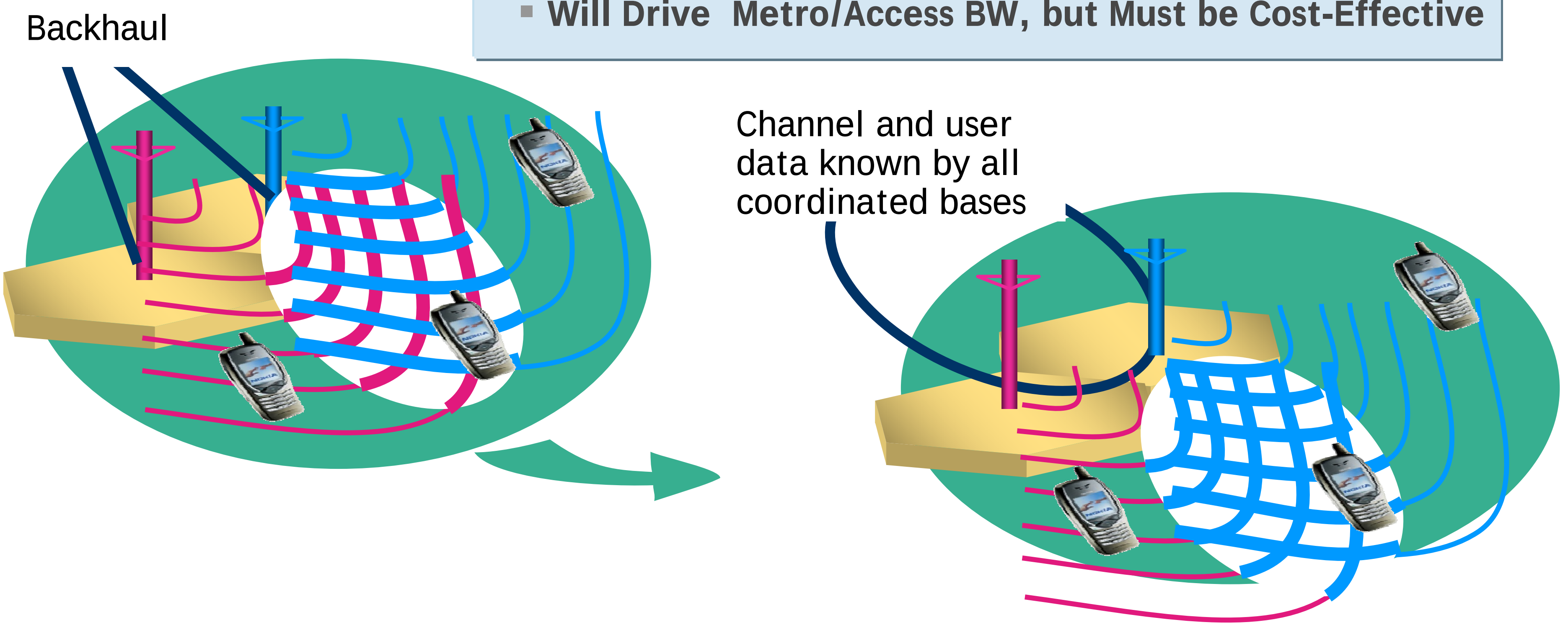
Communication Directions and Challenges

- **ONE Network**
  - Data/Optical, Wireline/Wireless Convergence
  - Ethernet (with WDM) Will Blur the Metro/Enterprise Boundary
  - Low-Cost Storage in the Network- a "Wildcard"
- **Broadband Mobile Use**
  - Ubiquitous, Smaller Cells (eg, home femtos) Will Drive Optical Backhaul
  - Use BB Wireline Network to Increase Wireless BW (Network MIMO)
  - Mobility is the "Friend of Optical"- Backhaul Critical
- **Global Total Presence**
  - Symmetric Bandwidth to End Users
  - Very High Resolution Video (3-D?) Displays
  - "Flattened the Globe" ➔ "Better than being there"
- **The Network:**
  - "Learns" How to Optimize Itself
  - Is the Computer; Is the Sensor
  - Is Power Efficient and Affordable!

Ubiquitous Mobility will Drive More Optical Infrastructure

Mobile Society that Needs to Stay in Touch

- Inter-base Coordinated Networks (Network MIMO) to Maximize Wireless Bandwidth
- Applicable to Any Wireless Network (3G, 4G, 802.11, etc.)
- Will Drive Metro/Access BW, but Must be Cost-Effective



Video of the Future?

Data Rates for 2D and Holographic Video Displays

HiDef 2D Video (1920x1080 pixels @ 24 fps):

1-2m display size, 1.2Gb/s uncompressed, **25 Mb/s compressed**

HiDef Stereoscopic Video (2 x 1920x1080 pixels @ 24 fps):

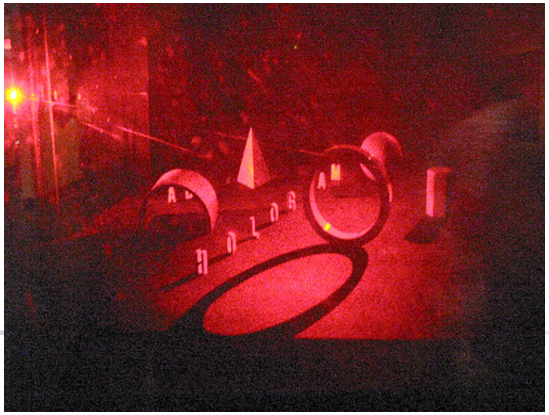
1-2m display size, 2.4Gb/s uncompressed, **50 Mb/s compressed**

HiDef Holographic Video - horizontal parallax only (400,000x1080 pixels @ 60 fps)

0.5m display size, 0.62 Tb/s uncompressed data rate, ~**60 Gb/s compressed**, >100 Teraflops for real-time computer-generated video holograms

HiDef Holographic Video- full parallax (400,000x400,000 pixels @60 fps)

0.5m display size, 230 Tb/s uncompressed, ~**23 Tb/s compressed**

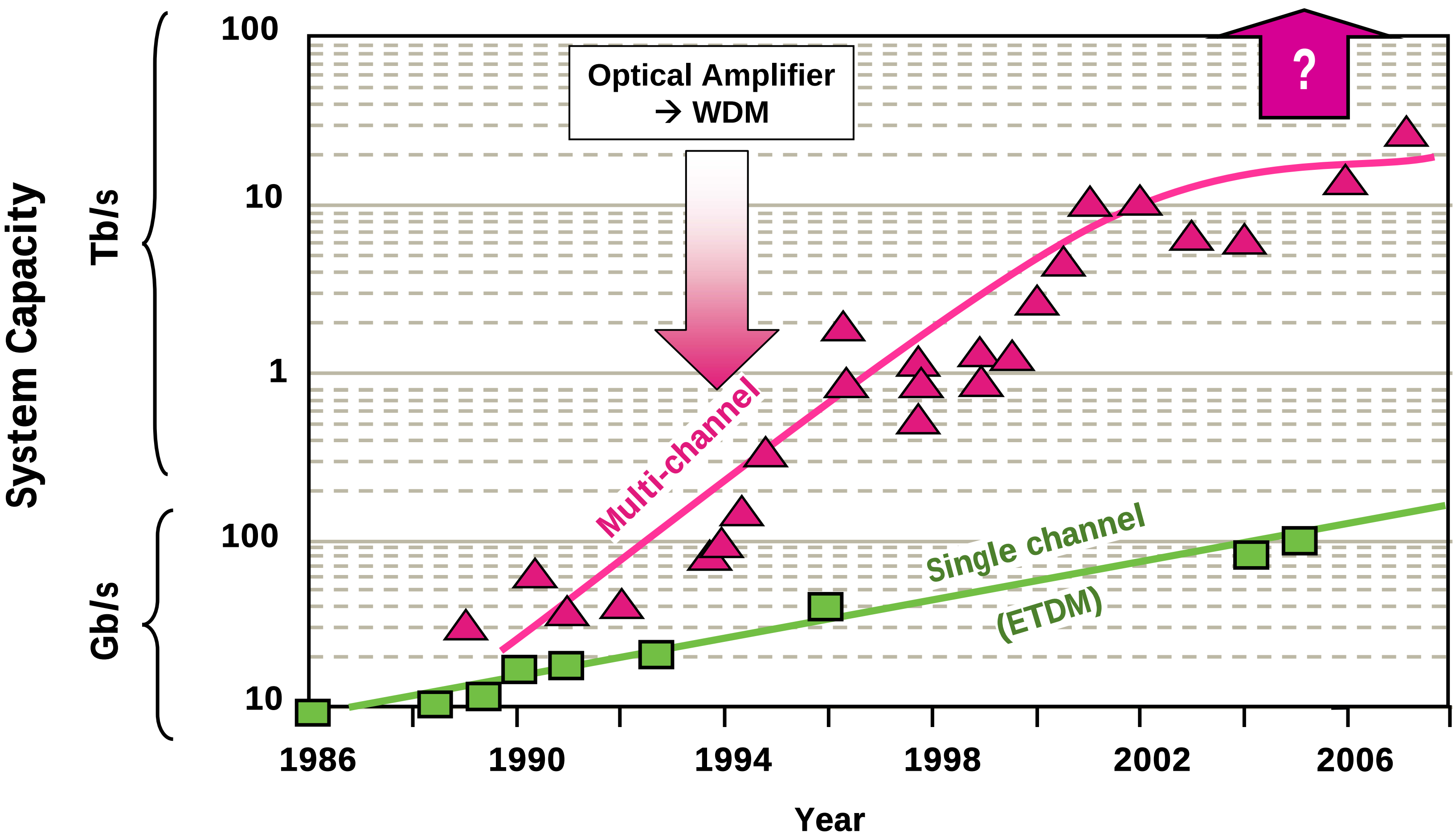


Courtesy: Randy Giles

Progress in Optical Transmission - Getting Another Factor of 50-100 on a single Fiber - Challenging and Exciting!

Optical Transmission Research Records: Slowing

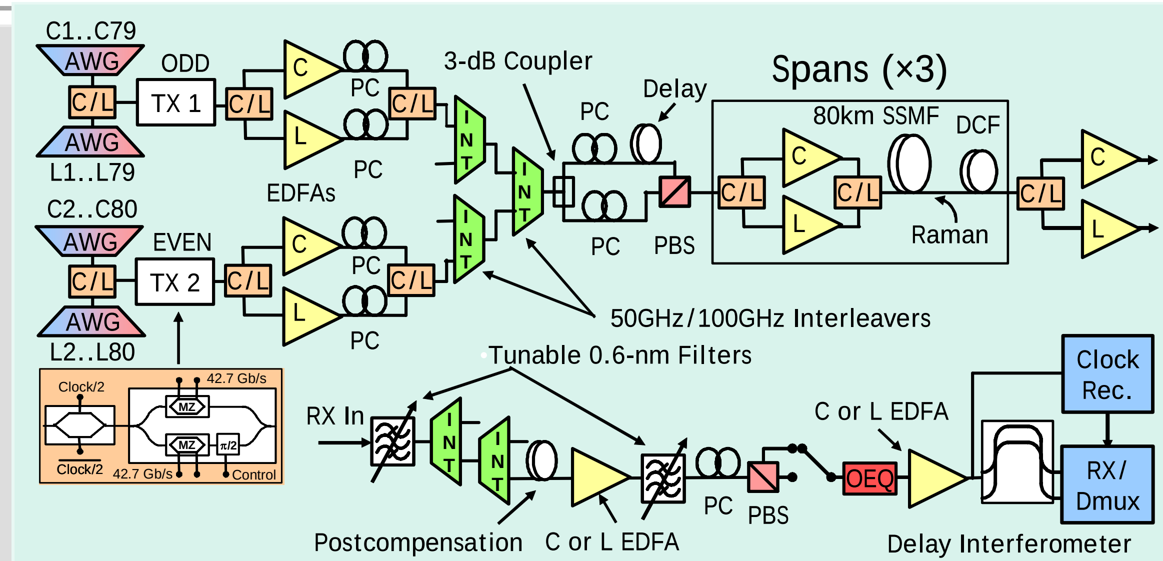
Research Records

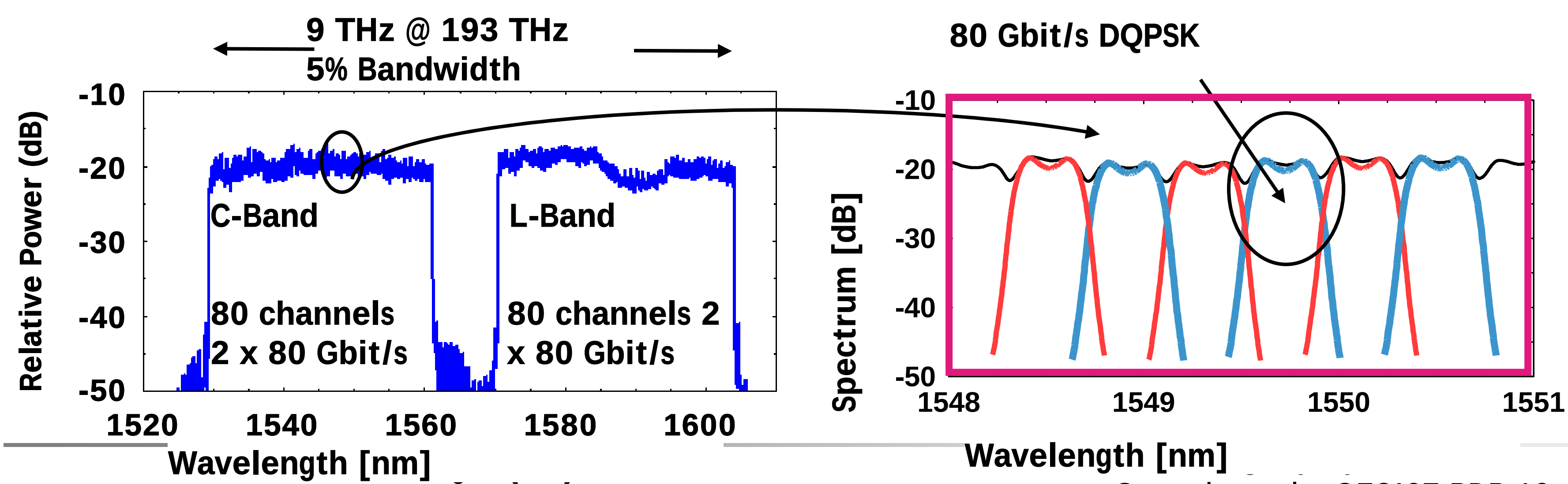


Courtesy- Peter Winzer

25.6-Tb/s Transmission Research Demonstration

- **160 WDM channels**
- C and L bands: 50-GHz grid
- Polarization multiplexing
- 42.7-Gbaud (85.4-Gb/s) DQPSK in each polarization yields 160 Gb/s in each WDM channel w/7% FEC
- **3.2 b/s/Hz spectral efficiency**
- 240 km (three 80-km SSMF spans)
- EDFAs + distributed Raman





Gnauck et al., OFC’07 PDP 19

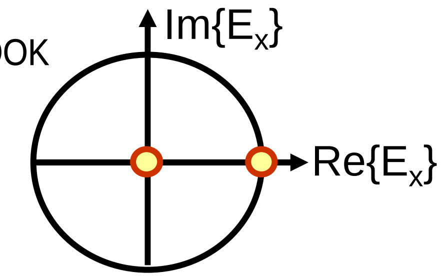
Advanced Modulation Formats for 100 Gb/s

1 bit/symbol

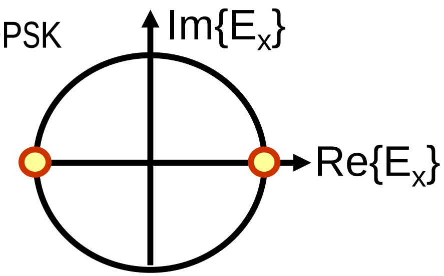
~112 Gbaud

(OOK, DB/PSBT, …)

OOK



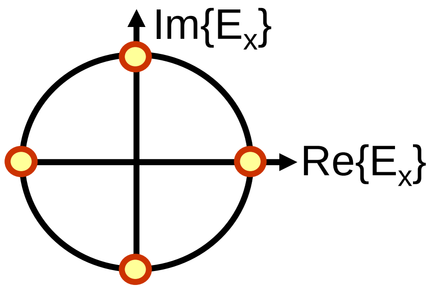
DPSK



2 bits/symbol

~56 Gbaud

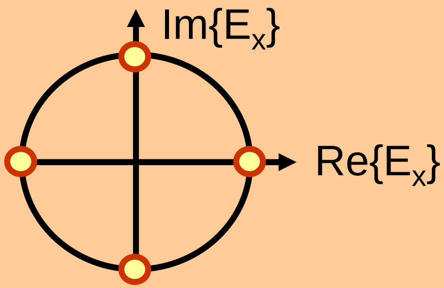
(DQPSK, pol-muxed OOK, …)

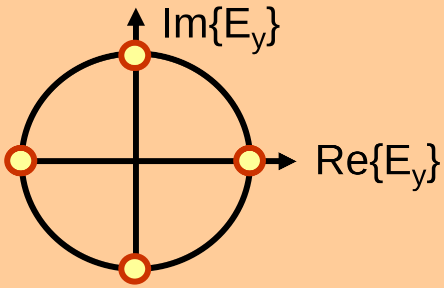


4 bits/symbol

~28 Gbaud

(pol-muxed (D)QPSK, 16-QAM, …)





E_x … Optical field, x-polarization
E_y … Optical field, y-polarization

Multi-symbol to Reduce Baud Rate > Reach

Lower Spectral Width to Reduce Impairments and Ability to Transit ROADM

Coherent and OFDM Encoding Also Attractive with Electronic Transmission Impairment Mitigation

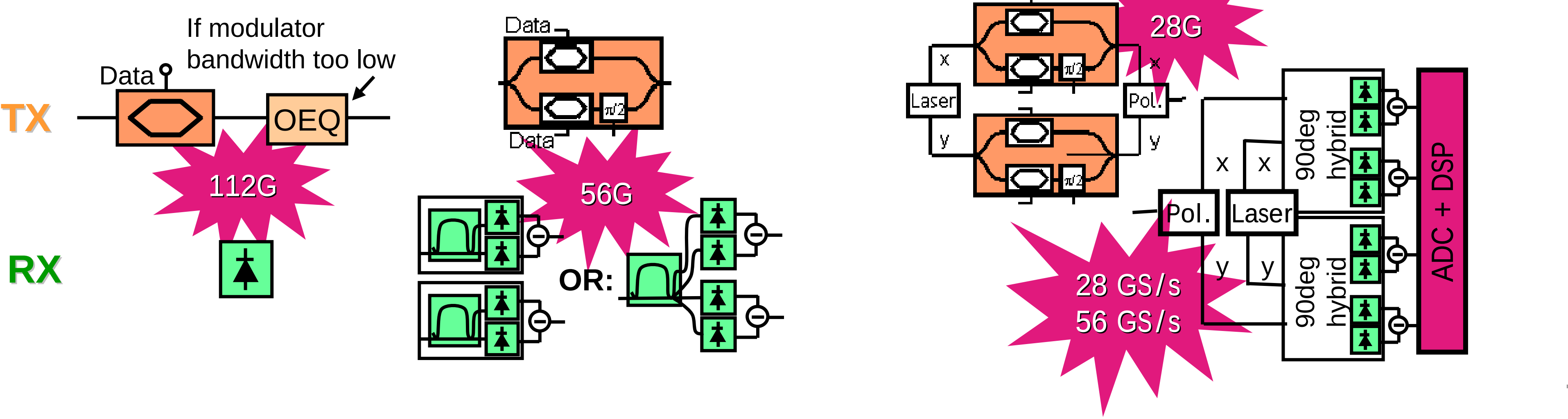
Multi-level Modulation Formats for 100Gb/s – Impairments & Complexities

1 bit/symbol	2 bits/symbol	4 bits/symbol	8 bits/symbol
~112 Gbaud	~56 Gbaud	~28 Gbaud	~14 Gbaud

Required OSNR

Tolerance to CD, PMD, filtering (ROADMs)

Hardware feasibility **Integration Essential!**

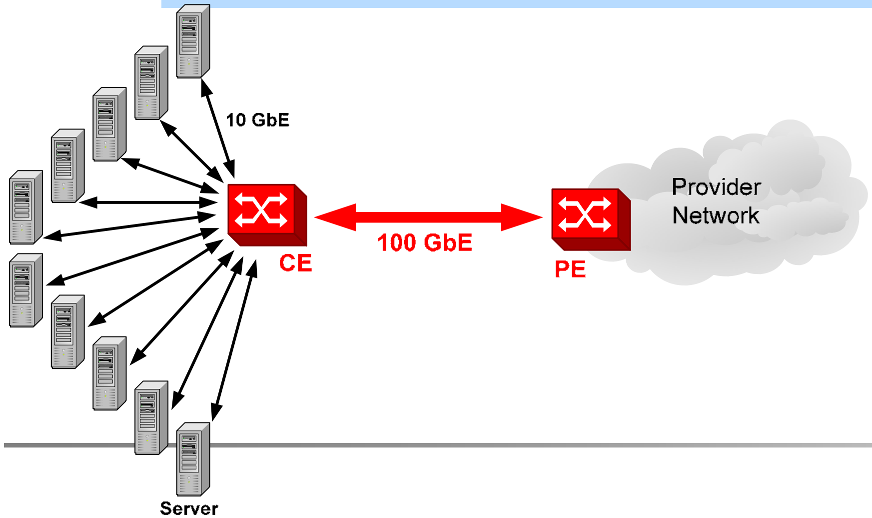


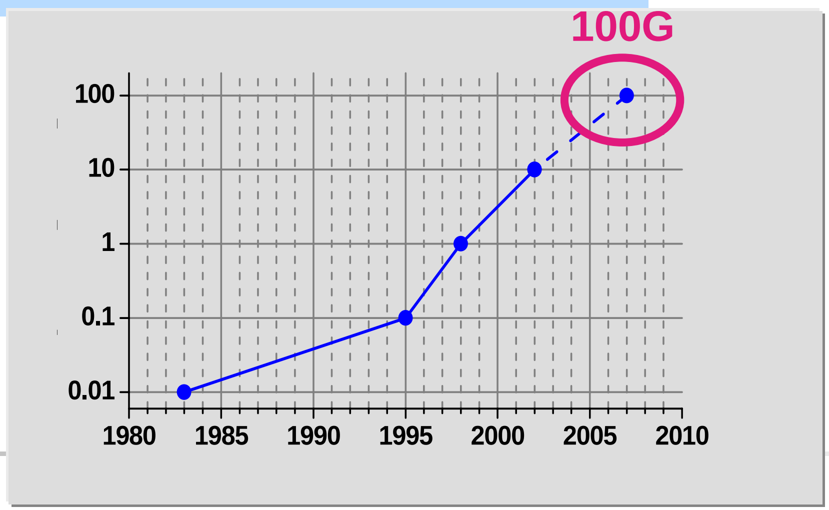
Courtesy: Peter Winzer

Next Gen Ethernet: 100GbE

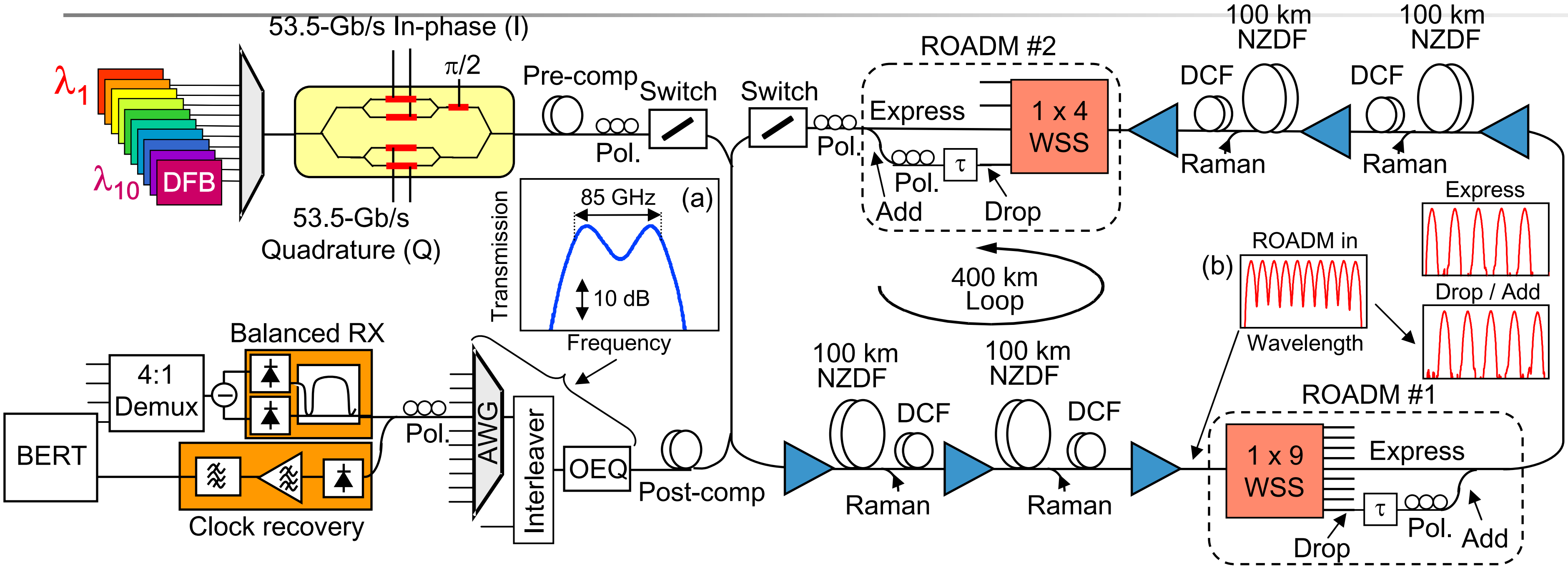
Why 100G Ethernet?

- Access rates of 10G now for Server Farms, aggregation into higher rates required
- More capacity per wavelength needed in the future core
- Growing demand for data traffic (IP TV/Video, etc.)
- Enabling higher port/switching capacities per footprint
- Follow the historical trend …





NRZ-DQPSK on 100-GHz grid over 1200 km and ROADMs



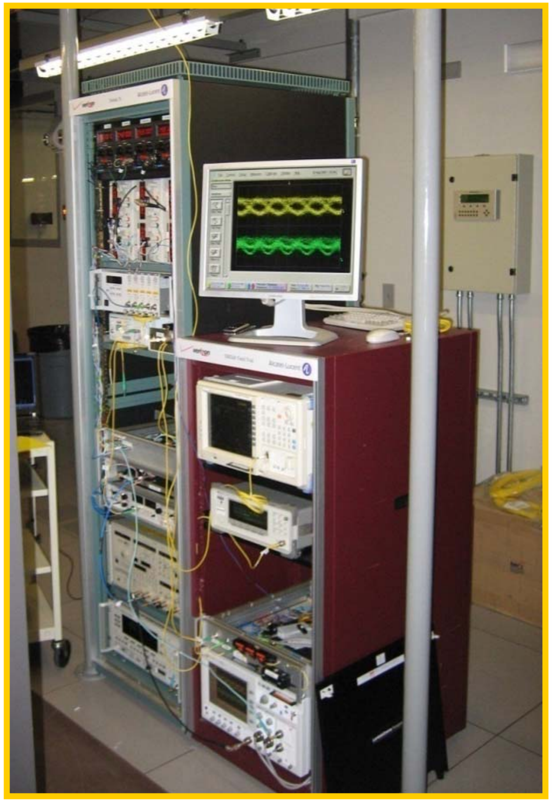
- **1.0 Tb/s capacity (10 x 107 Gb/s)**
- **High spectral efficiency, 1.0 bit/s/Hz, (100-GHz spacing)**
- **No polarization multiplexing**

P. Winzer et al., OFC 2007

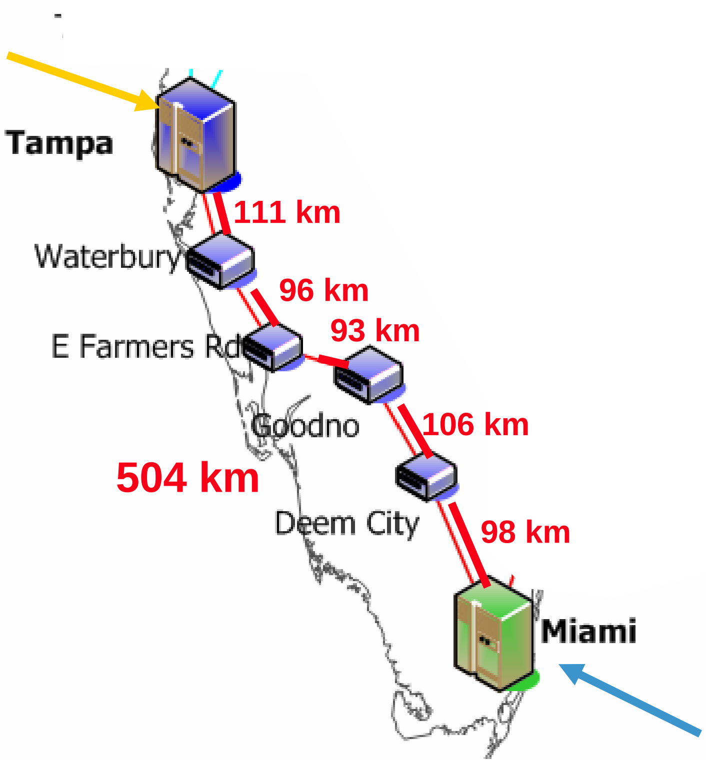
Network Upgrade at 100 G- Realizing the Value of Wavelength Routed Ring and Mesh Networks

100 Gb/s DQPSK Field Trial on Legacy ROADM Network

Leveraging Optical Network Value via Line Terminal Upgrade



100G Transmitter at the Tampa Central Office



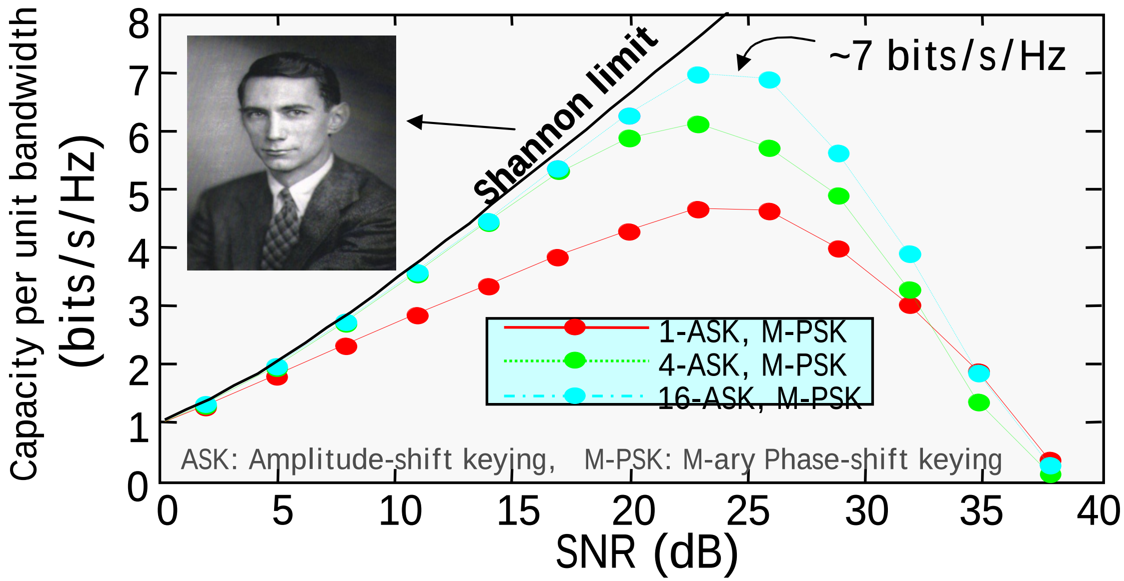
503-km Verizon field route operating LambdaXtreme®

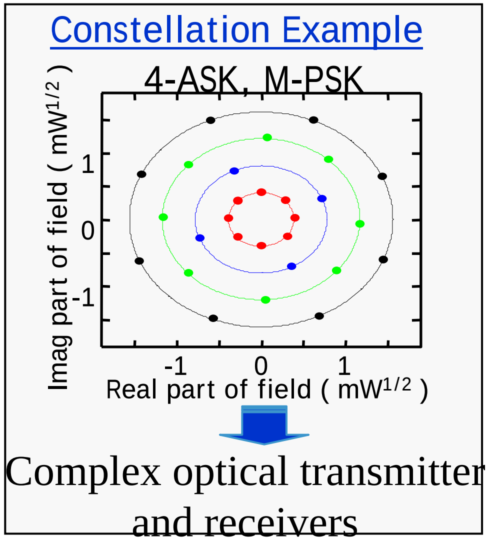
100G Receiver next to LambdaXtreme® at the Miami Central Office

The Next Factor of 20-40 Will be Very Challenging!

Fiber Capacity Estimate

Capacity per unit bandwidth (spectral efficiency) for 2000-km transmission





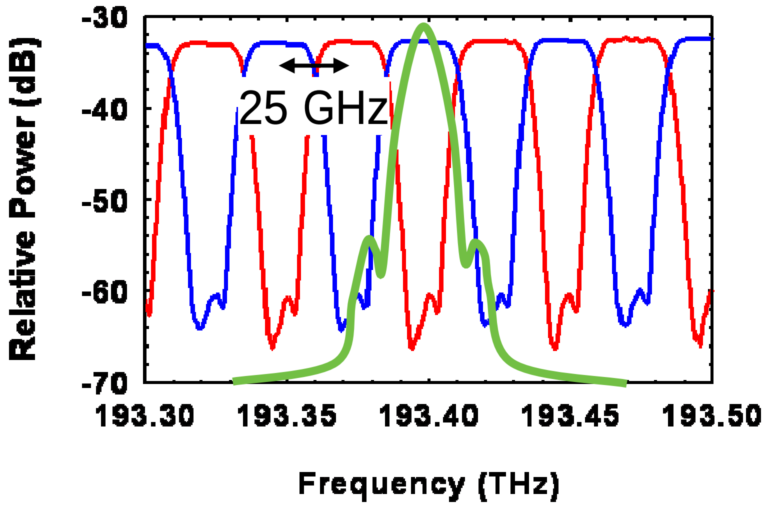
- **For 2000 km, a spectral efficiency of <u>~7 bits/s/Hz</u> per polarization can be achieved which corresponds to an increase of about <u>one order of magnitude</u> in spectral efficiency over <u>commercial systems</u>**
- **Deployed systems can transmit ~5 Tb/s over ~2000 km. For such a distance, the capacity limit of fiber is expected to be ~500 Tb/s or <u>~100 times the capacity of commercial systems</u>**

Courtesy: Rene Essiambre

Results Obtained Using 112-Gb/s 16-QAM

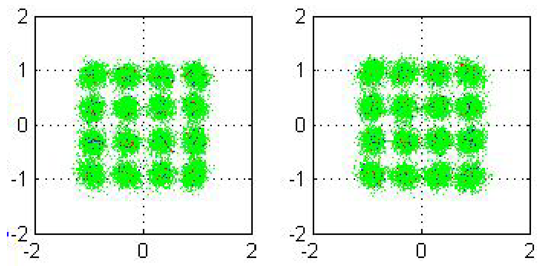
- ROADM concatenation & 300-km transmission on a *25-GHz WDM grid*
  - 1 dB penalty for 7 ROADMs

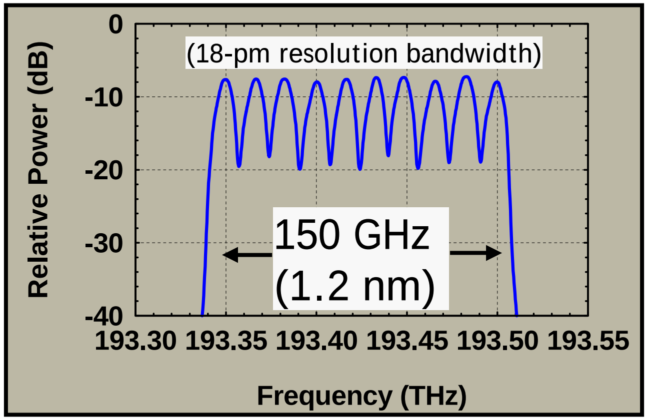
[Winzer et al., ECOC'08]



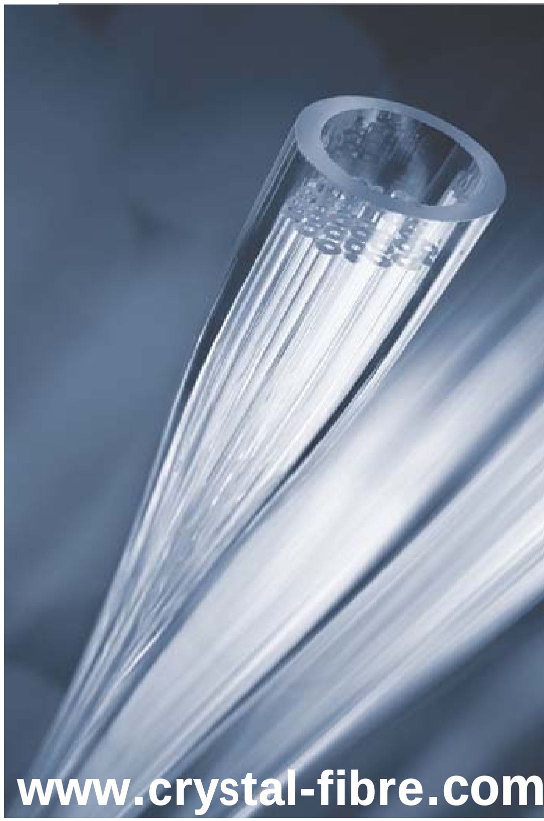
- *Record spectral efficiency* (6.2 b/s/Hz) and 630-km transmission
  - 1 Tb/s in 1.2 nm of optical spectrum

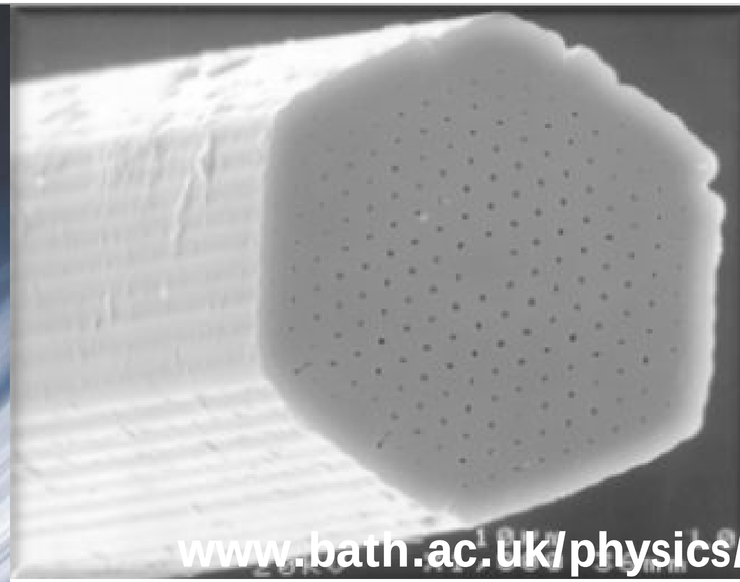
[Gnauck et al., OFC'09]

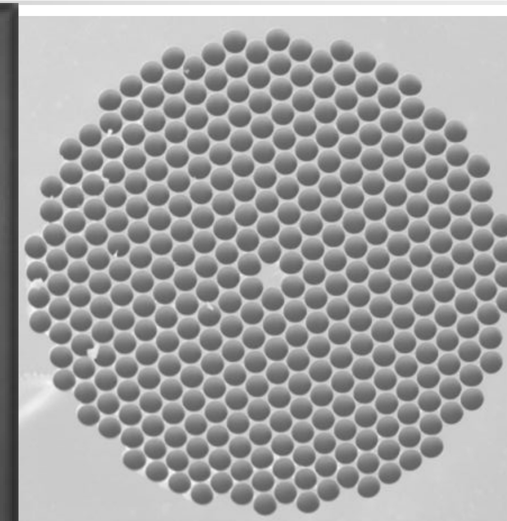


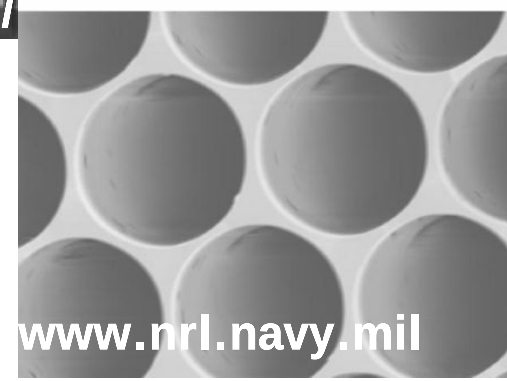


Fiber and Amplifier Advances will be Essential!









Courtesty: Herwig Kogelnik

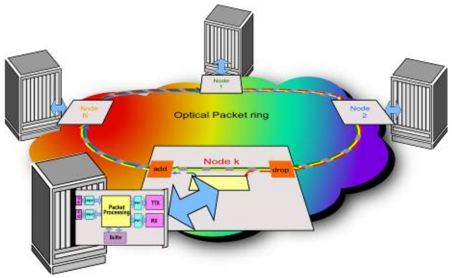
Expanding the Role of Optics in Networks

Real Time Switching/Routing

What's Next for Photonic Switching in the Network?

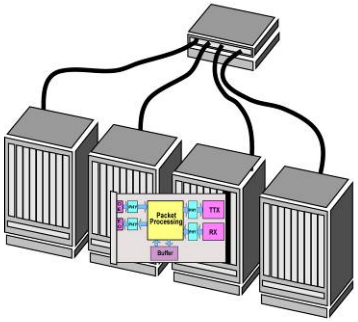
First, some learnings from Today's Optical Networks

- **Why WDM Networks Prevailed?**
  - **Reduced Network and Operations Cost**
- **Key Optical Switch Characteristic?**
  - **Flow switch, Bit rate agnostic, slow (ms) acceptable**



Reasonable next steps for photonic switching?

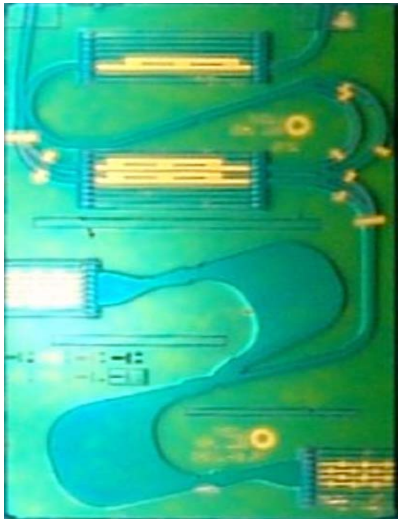
- **Address New Converged (WDM/Packet) Transport Architectures**
- **Explore the role of photonics to scale packet switch/ routers**
- **Explore and drive optical technologies that cost-effectively enable these directions**

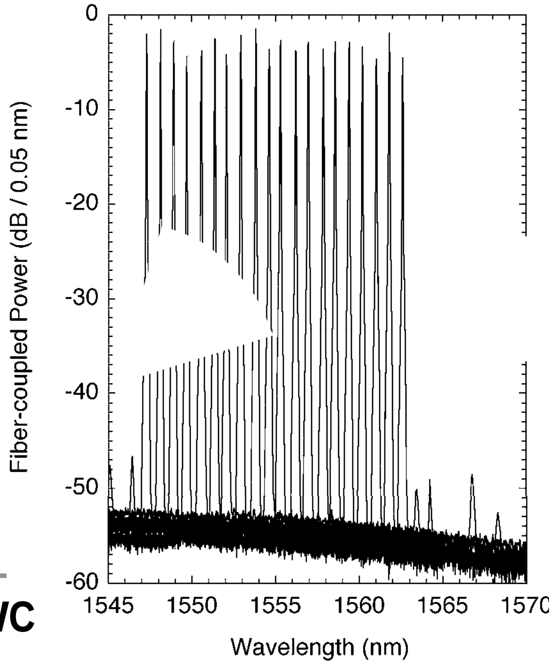


Transforming The Way We Use Light:

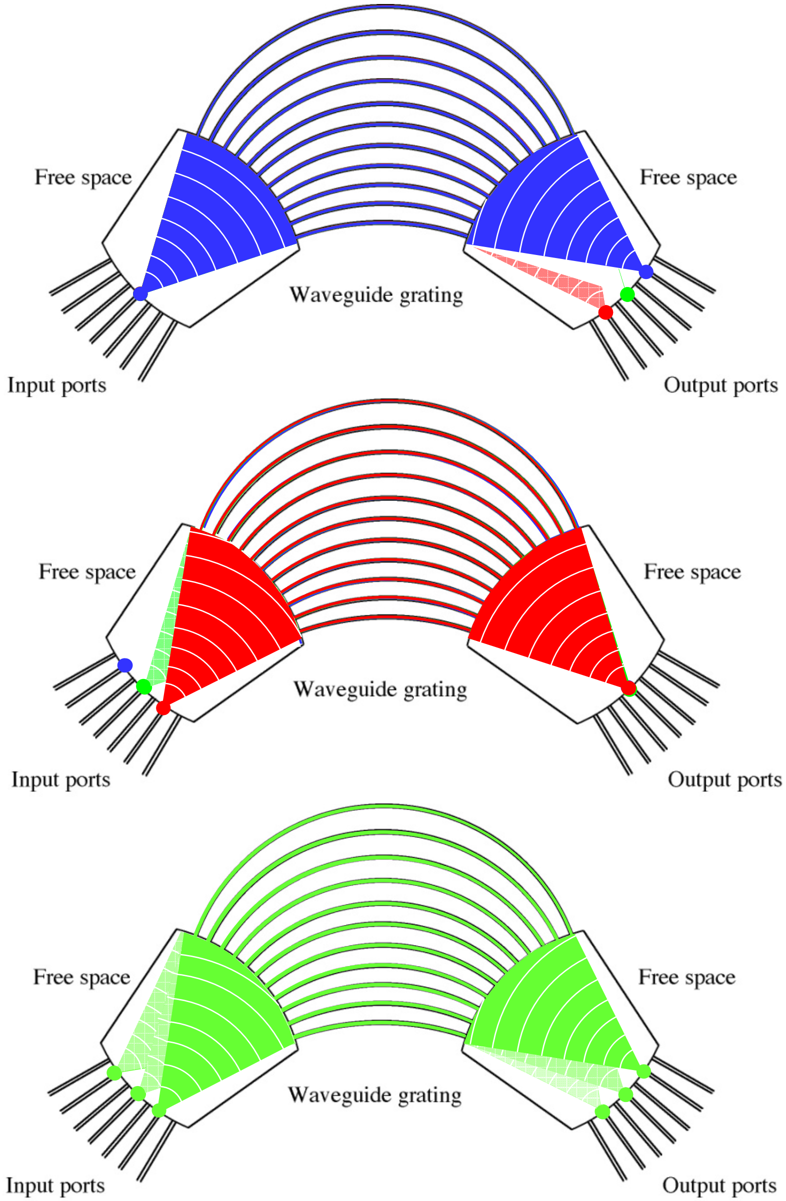
Next Generation Packet Routers Wavelength Switching

- Arrayed waveguide grating (AWG)
  - 2D integrated diffraction grating
  - Commonly used as optical Mux/Demux
  - Cheap piece of glass

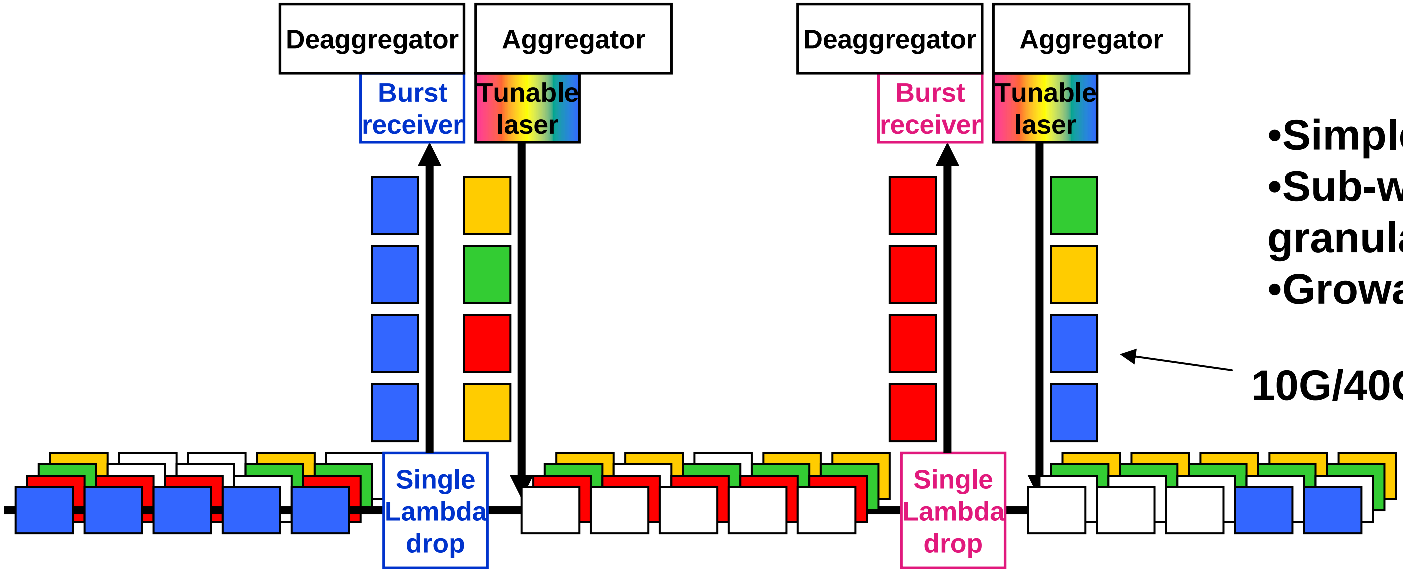




Tunable 20-channel WC



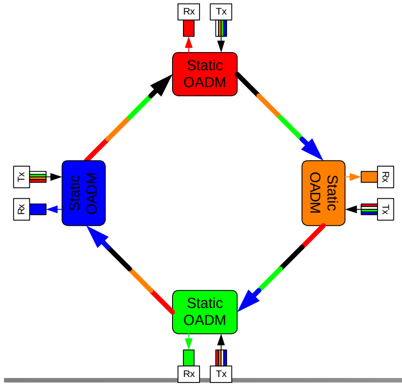
Time-Multiplexed WDM: Ring Architecture with WDM Scalability and TDM/Packet Granularity



- Simple optical Add/Drop.
- Sub-wavelength granularity.
- Growable to full WDM.

10G/40G Data Envelopes

T-WDM Ring:



N-Node Ring comparison:

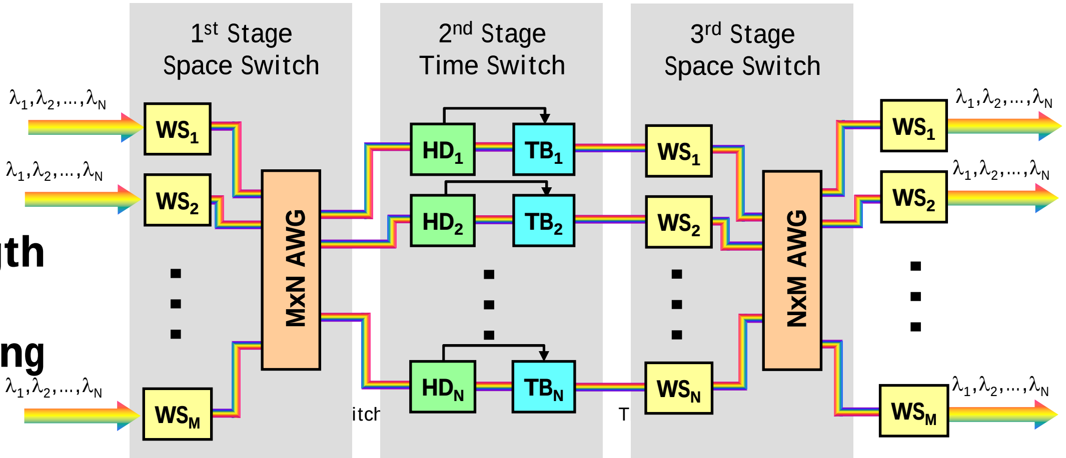
	Bandwidth Granularity	# of Transmitters /Receivers	Bandwidth Efficiency	Scalability
SONET Ring	50 Mb/s	N	1/N	10/40 Gb/s
T-WDM Ring	50 Mb/s	N	Close to 100%	5 Tb/s
WDM Ring	10 or 40 Gb/s	N(N-1)	100%	5 Tb/s

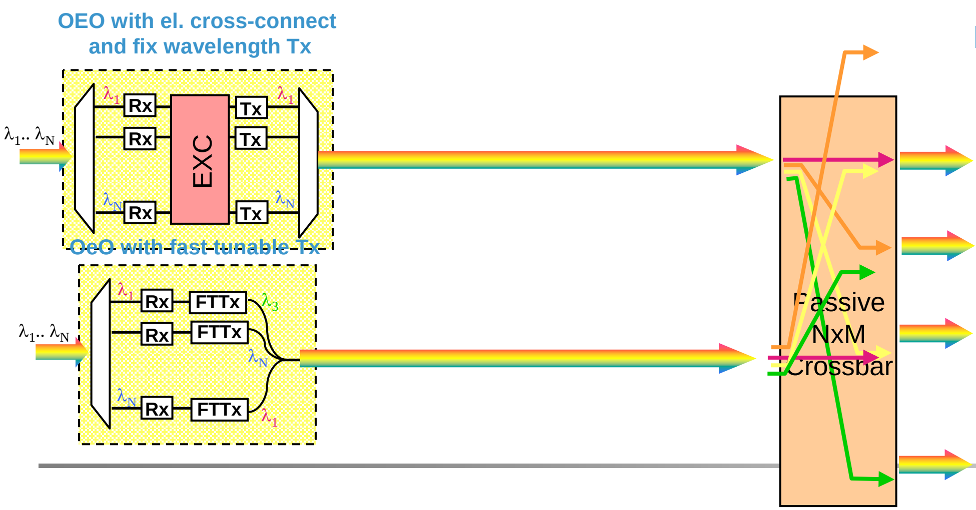
Zirngibl, et al, Bell Labs, Alcatel-Lucent

Expanding Optical Switching to the Packet Layer

High-capacity photonic packet switch
Data in the Optical Domain-Network (DOD-N)

- **Load-balanced architecture for high-capacity optical packet switch**
  - **3-stage architecture**
    - **Fast switching in the wavelength domain**
    - **Simplified distributed scheduling**
    - **Highly scalable**
  - **Well suited for optical implementation**





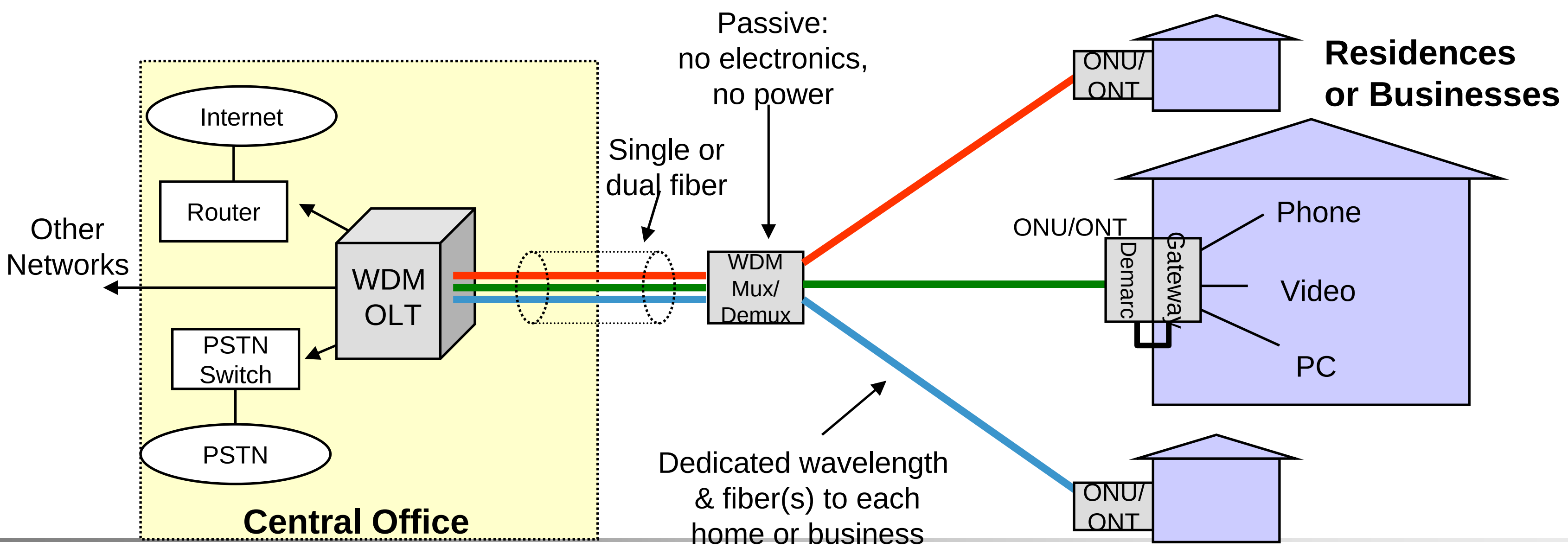
- **Optical fabric based upon λ-switching and wavelength selective crossbar**
  - **How to do it with off-the-shelf parts**
  - **How to skip the electronic cross-connect**
  - **How to skip OEO with an all-optical monolithic chip**

Courtesy: Dave Neilson
Pietro Bernasconi

FTTP Evolution: WDM PON

Low-cost, integrated WDM technologies are key to cost-effective very-high broadband services to the home

- **Different bit rates, protocols, and services for each sub**
- **Easy to upgrade sub without affecting others**
- **Good subscriber isolation**
- **Consider PON for Metro Networks?**



Extending Optics into the Home?

Extending Optical Reach into the Home?

Versatile BB In-Home Networks

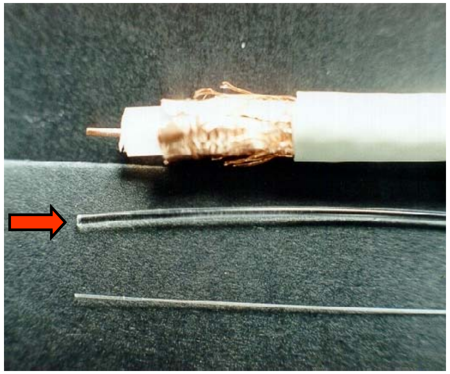
Converged in-home backbone network, integrating wired & wireless services

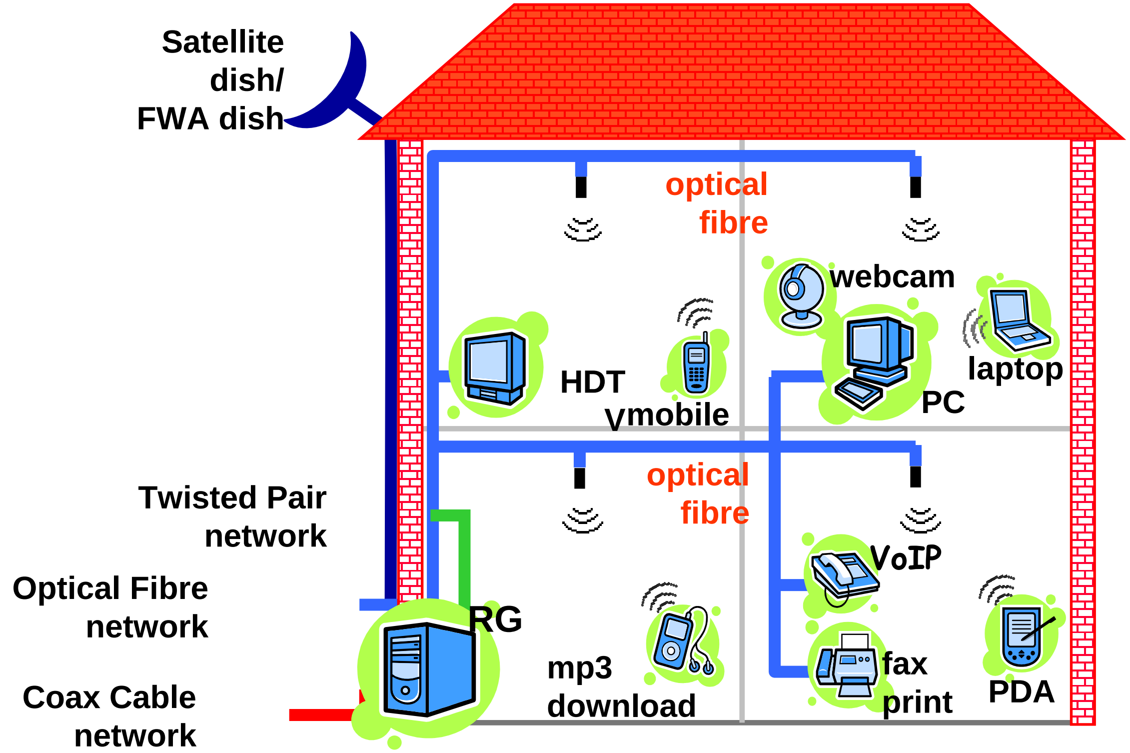
- reduces installation and maintenance efforts
- eases introduction and upgrading of services
- integration e.g. by WDM

coax

POF

SMF





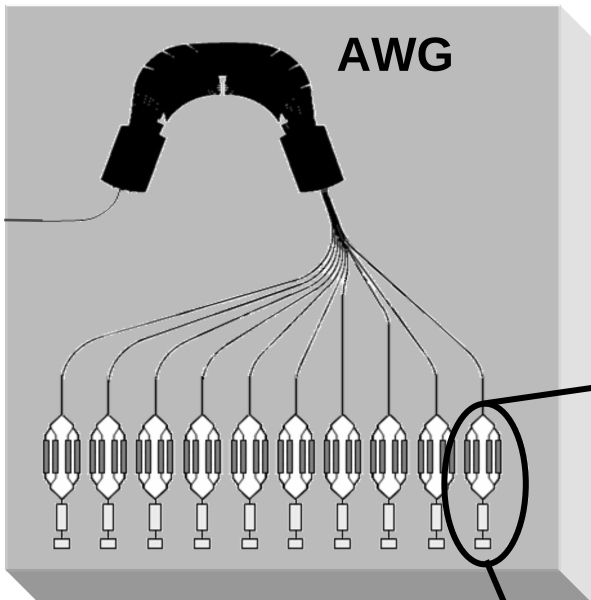
➡ Converged In-Home Network on Plastic Optical Fiber

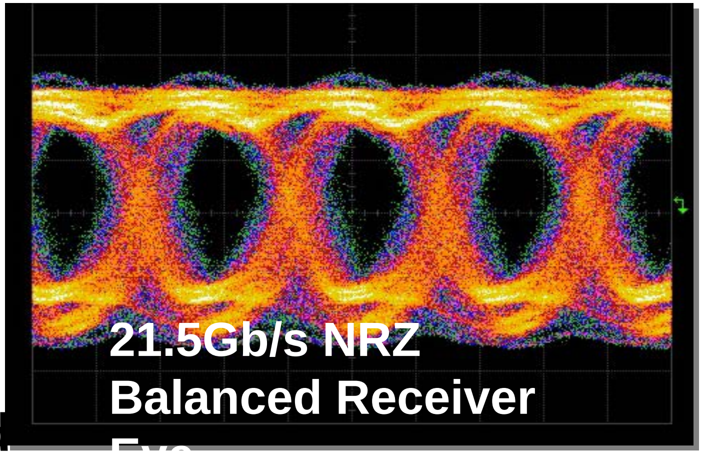
Courtesy: Ton Koonen

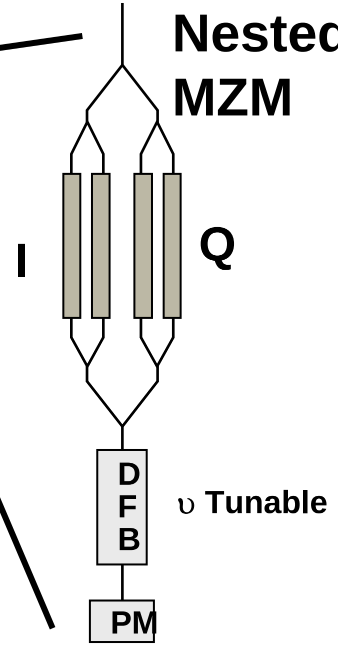
... Integrated Technologies Will be Key...

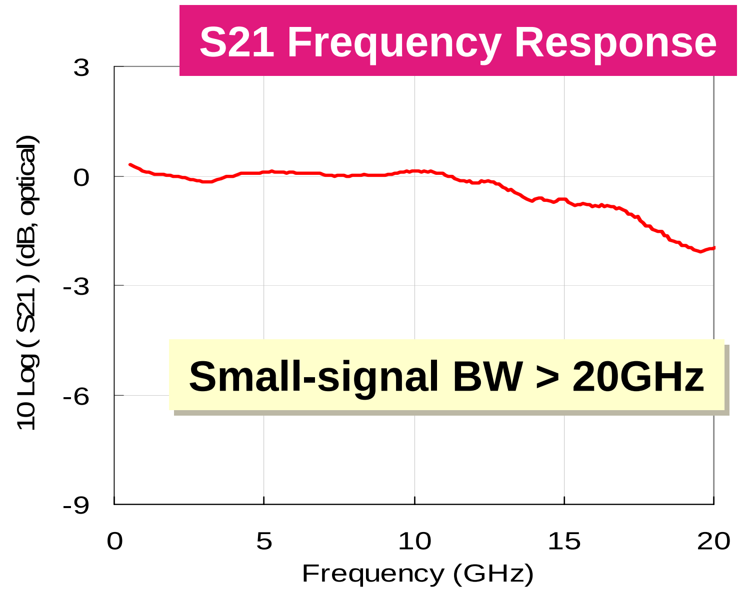
but which one?

Large-Scale DWDM DQPSK Tx PIC 10 Channels x 40 Gb/s









10 frequency-tunable DFB lasers with backside power monitors

10(I) + 10(Q) nested Mach-Zehnder modulator pairs

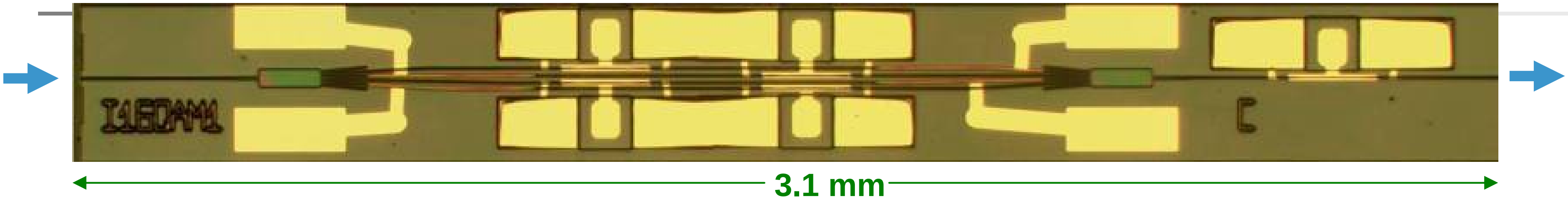
1 AWG

111 integrated elements in total on chip

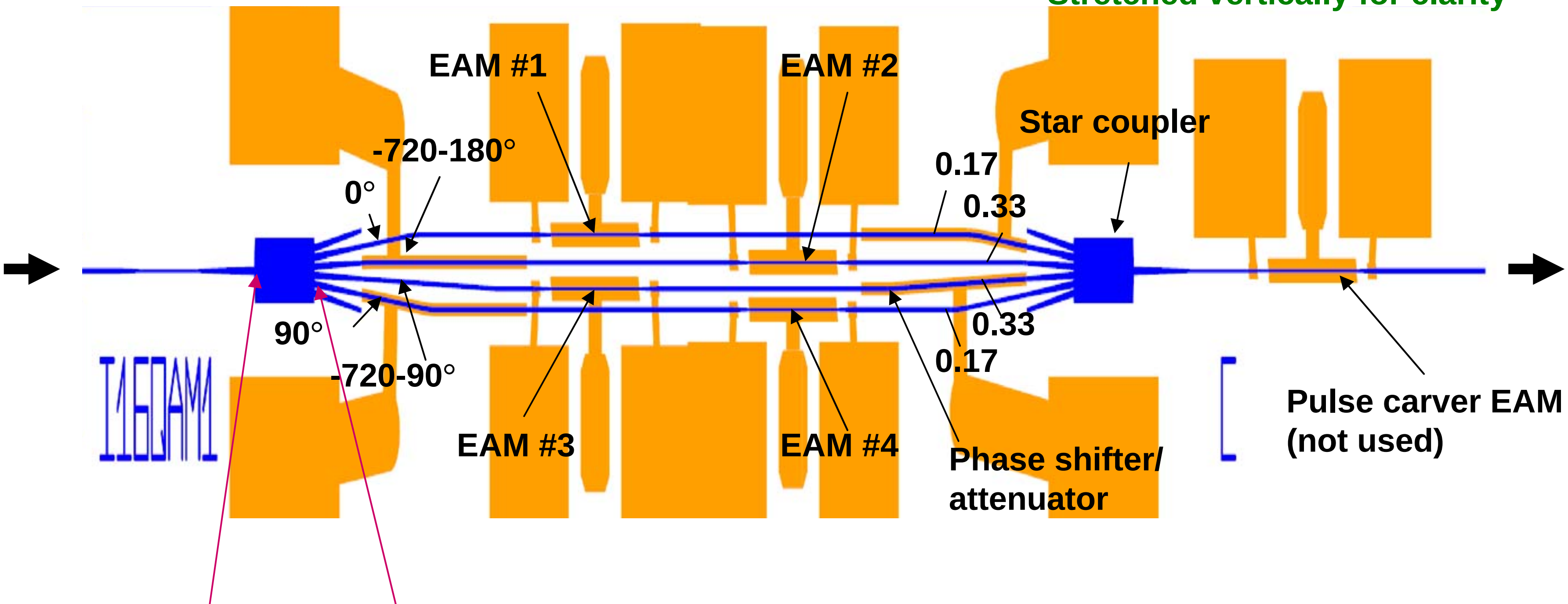
infinera

Courtesy: Dave Welch, Infinera

16 QAM Modulator PIC



Stretched vertically for clarity

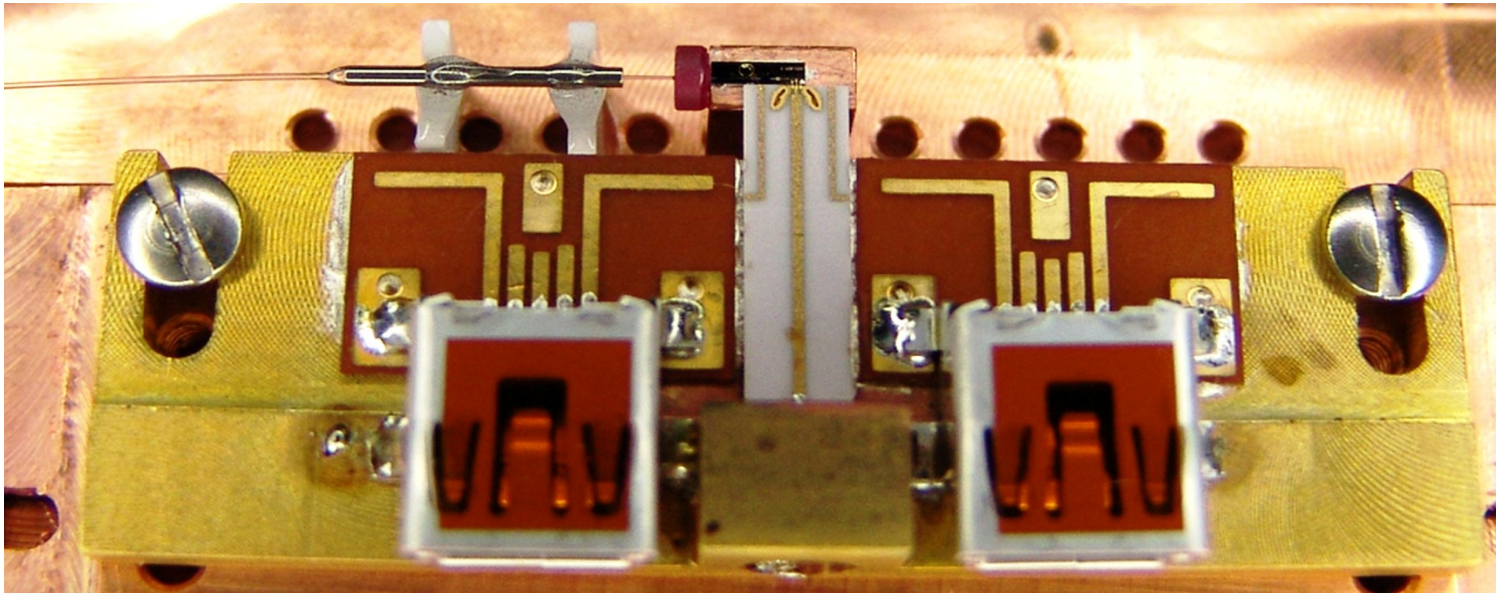


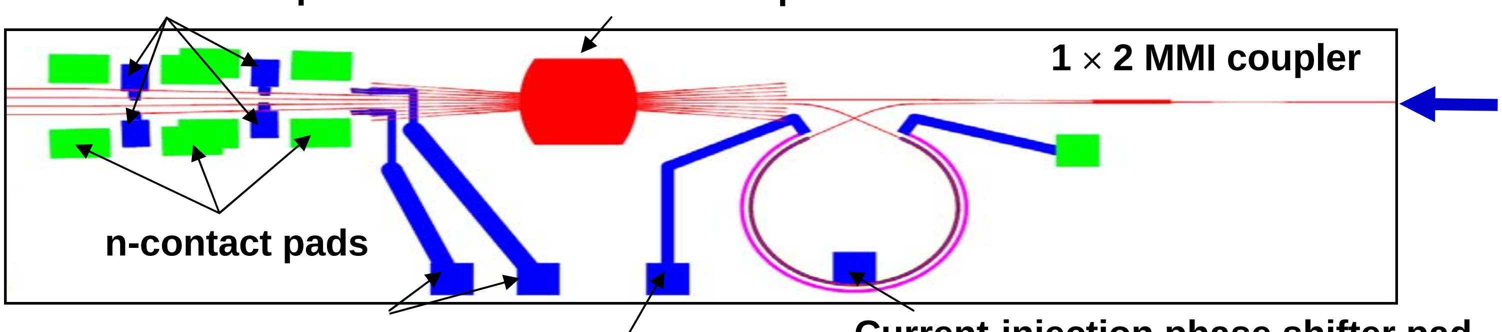
Use same output inlet width for all four ports.
Input inlet width selected to achieve the 1:2:2:1 power splitting ratio.

The phase shifters were used only for testing and were *not* used in the experiment

C. R. Doerr, et al., OFC, PDP20, 2008.

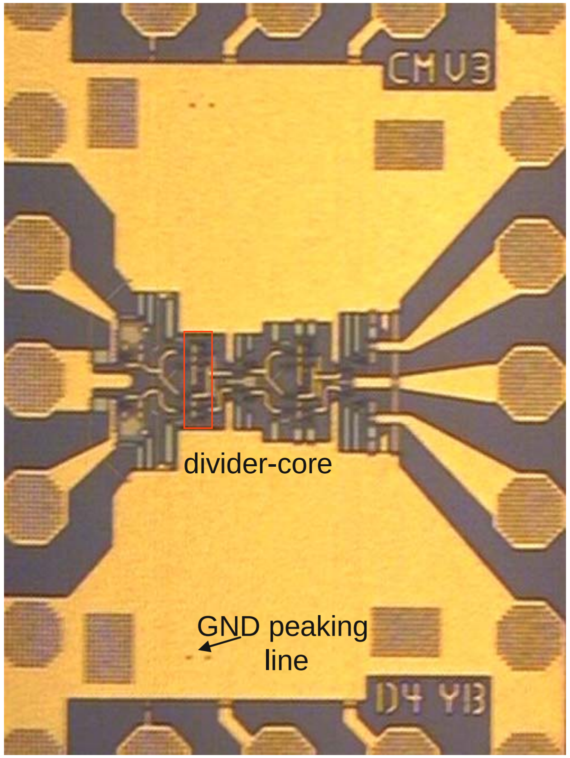
Monolithic InP 107-Gb/s RZ-DQPSK Receiver

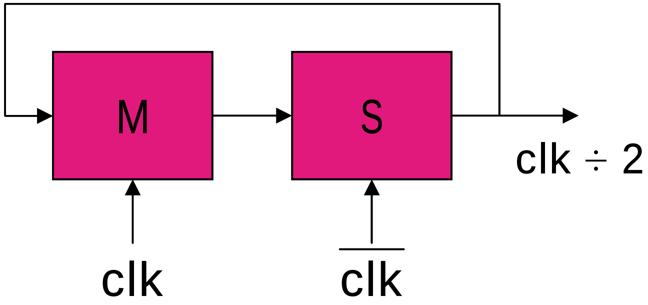


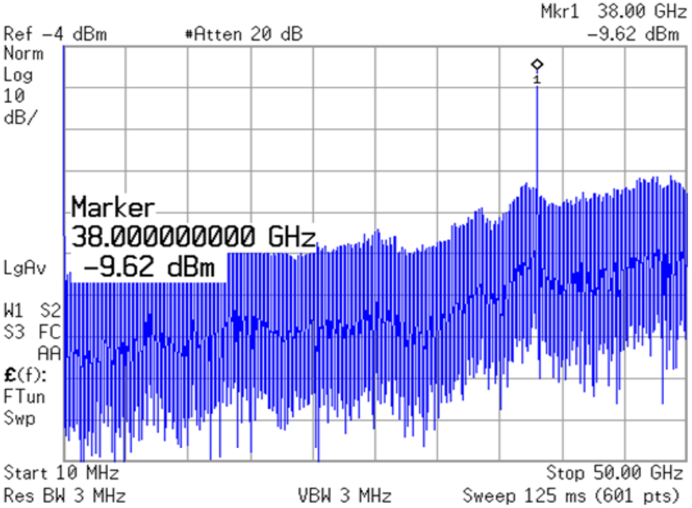


C. R. Doerr et al. OFC 2008

100 Gb/s Digital Circuits
InP D-FF up to 152 GHz clock speed







- Static divider ÷ 4
- 38 x 4 = 152 GHz clock speed
- Power consumption 25 mW/latch at 100 GHz
- Critical building block for MUX / DEMUX , CDR, etc.

N. Weimann, et al., IPRM 2008

Silicon CMOS Photonics Technology

Single Laser Powers 4 Lanes

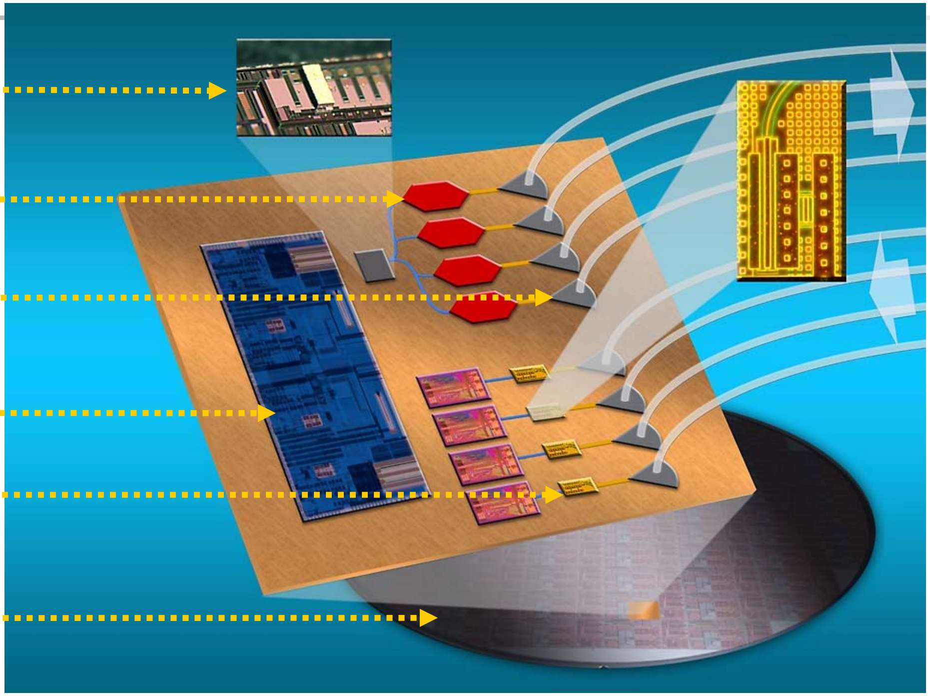
On-Die Modulators

Fiber-to-the-Chip Coupling

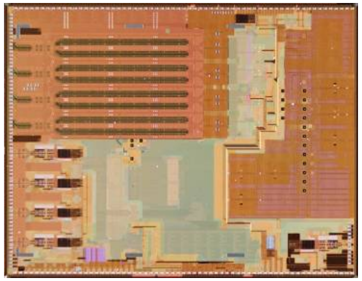
Integrated Electronics

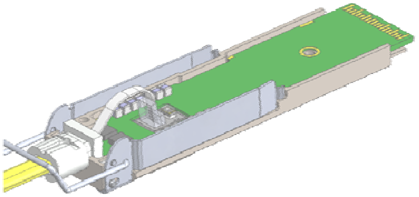
Integrated Photo-Detectors

Wafer Scale Testability



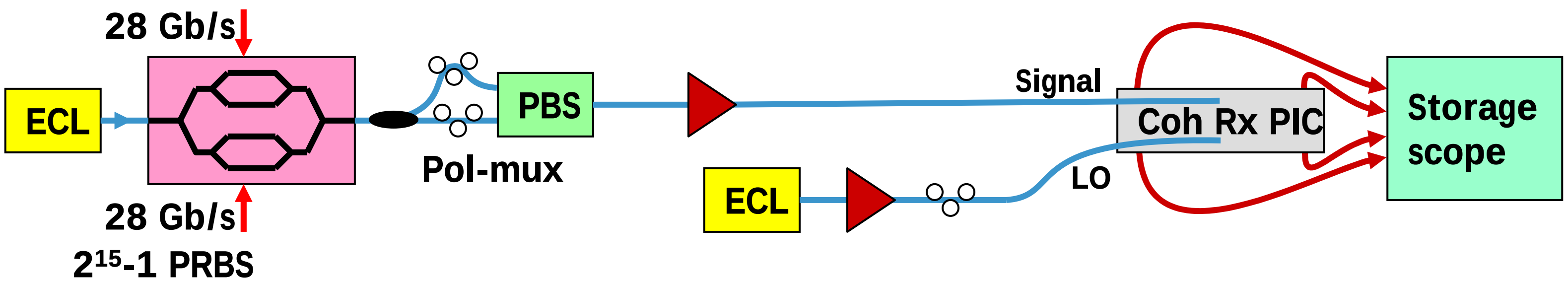
Implemented on a monolithic CMOS die and packaged in standard connectors

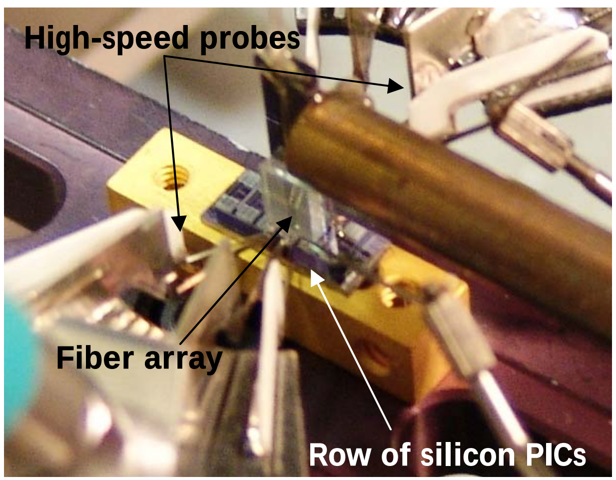


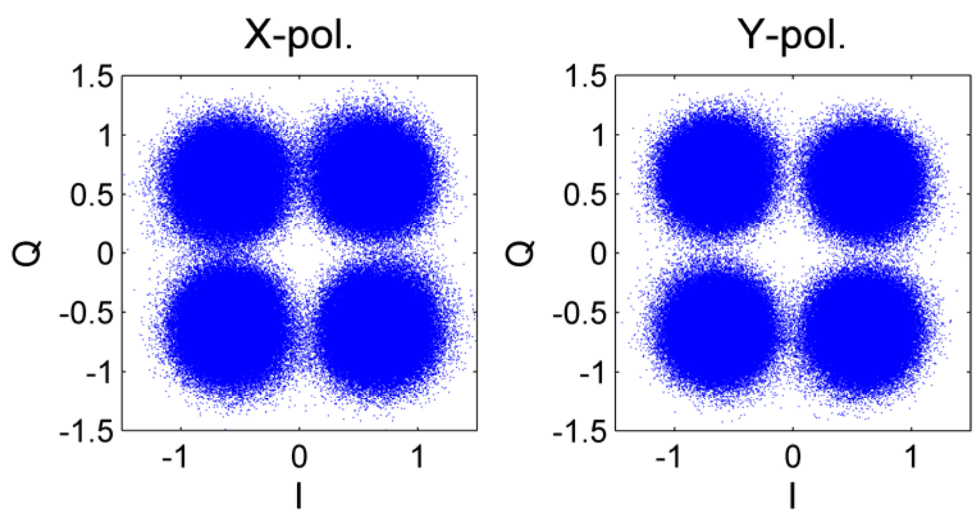


Courtesy- Cary Gunn, Luxtera

Silicon Coherent Receiver PIC







112-Gb/s PDM-QPSK

C. R. Doerr, et al., PD paper, OFC 2009.

Concluding Remarks

The Message

- Over Last the 10 years, with WDM, We have increased Commercial Optical Systems Capacity by ~100 and deployed Wavelength Routed Optical Networks to Reduce Network Cost and Enable Graceful Upgrade
- Over next 10 years, We Expect Capacity Needs to Increase another 50 to 100 times. Can We Meet That Challenge in Cost-Effective Solutions that our Industry and Society have come to Expect?
- Research, Inventions and Integration Required! The Best of Optics and Electronics; Integration for complex active functions and lower cost; improved amplifiers and/or fibers; Optimization Algorithms
- Demand will Challenge Switch/Routing- Optics will likely play a role in the solution
- When Demand in the Home Requires it, WDM PONS Will Offer Ultra-Broadband Services yet to be Devised
- A Challenging and Exciting Decade Ahead!

Thank You!