The quest for high capacity, long reach, industrial strength networks

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The 12th Annual International Workshop on Innovating the Network for Data-Intensive Science (INDIS)

Quest for the Bit

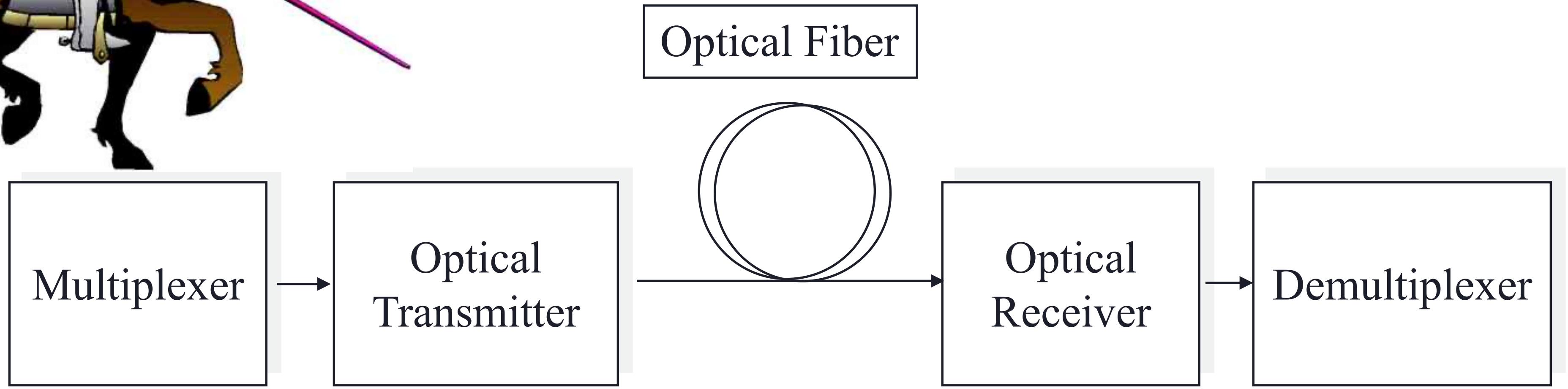
PUBLIC USE

Industrial strength Quest

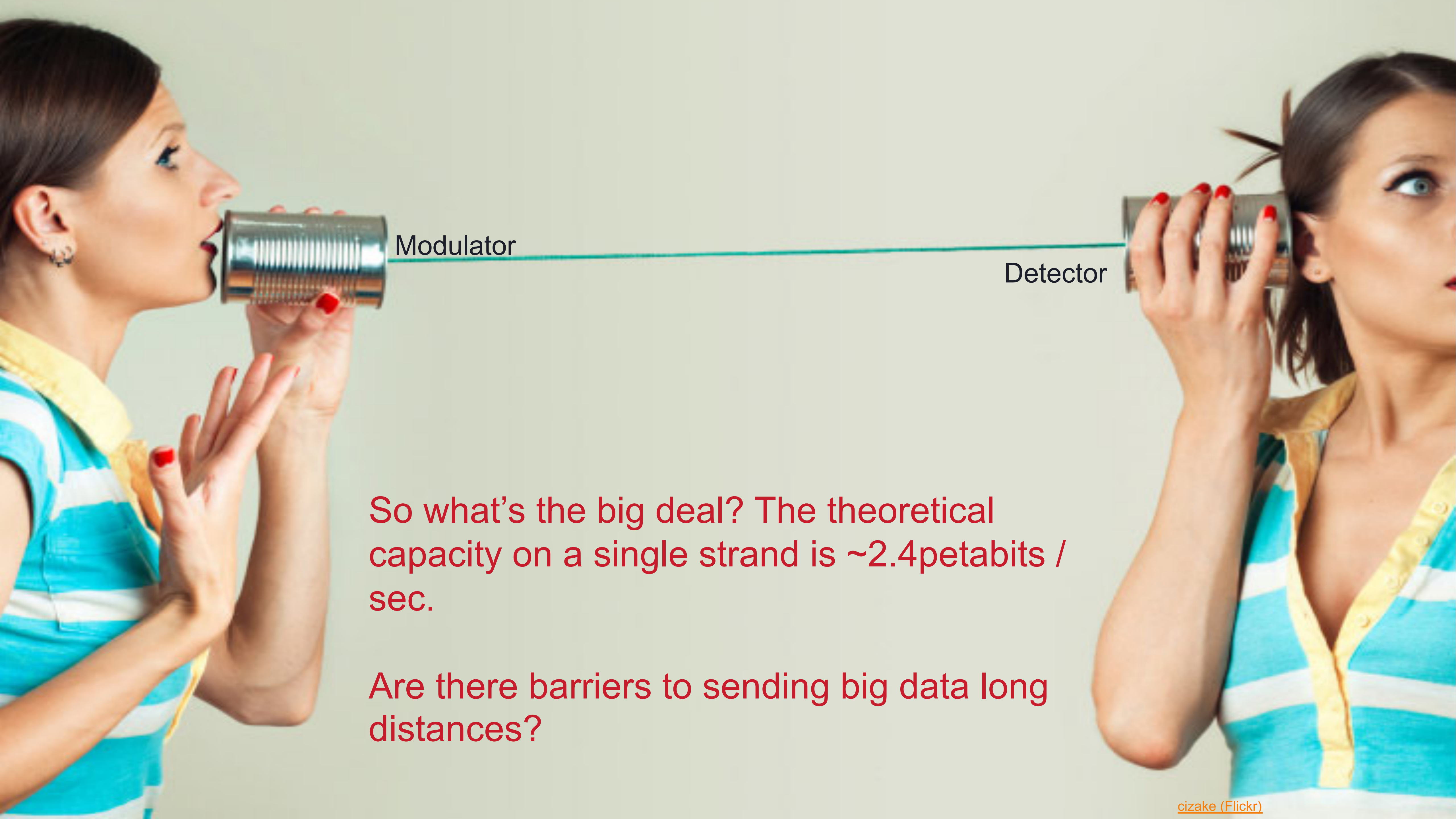
SCinet top 5 network vendors spent $15.8b in R&D in 2024
Many foci, Data Centre interconnection, Ai network automation, Cloud interconnection, Routing & Switching +++

This story is about the Quest to move bits.

The Quest



Communicate more bits, farther, for less cost.



So what’s the big deal? The theoretical capacity on a single strand is ~2.4petabits / sec.

Are there barriers to sending big data long distances?

cizake (Flickr)

Physical Barriers

Noise

noise

- **Early fibers had losses measured in dB/meter.**
- **Given the very finite amount of optical power that could be coupled into the fibers, received powers quickly became very low.**
- **Thermal noise in the receiver limited the bandwidth and distance for optical transmission.**
  - E.g.   1 Mb/s along 10 meters, experiments at Standard Telecommunication Lab (STL) Harlow Labs

ciena

Overcoming the Noise Barrier

Fiber loss was reduced to 2.5 dB/km

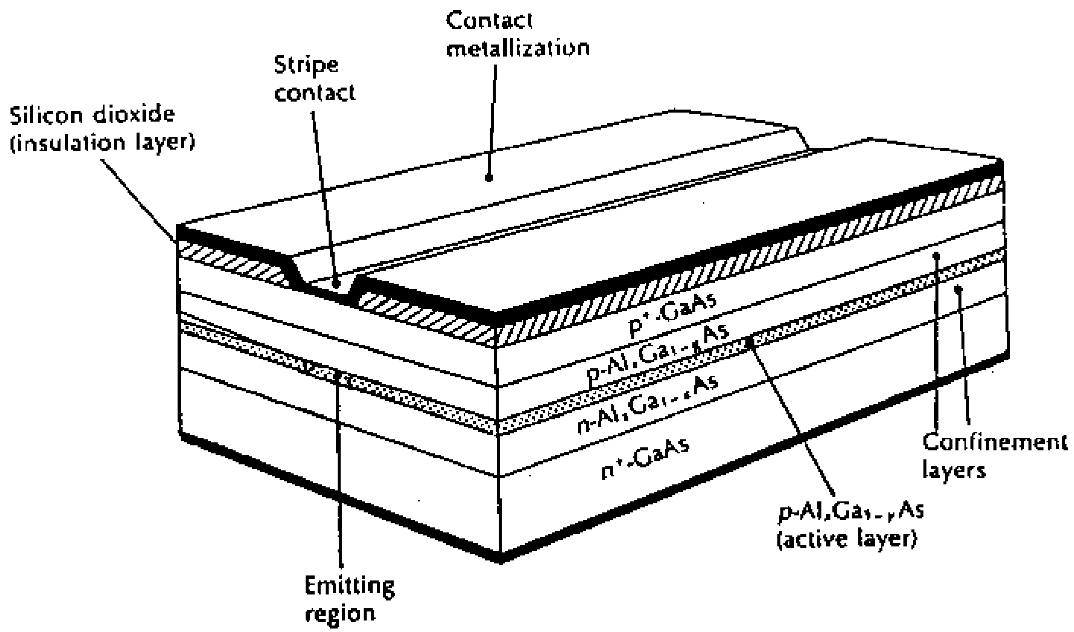
- Vapour deposition methods of creating pure glasses
- Developed by Corning and ATT

GaAlAs Semiconductor lasers

- Small, reliable, inexpensive
- Coupled a milliwatt of power at 850 nm
- Developed by ATT

Silicon Avalanche Photodiodes

- High gain: One photon triggered ~200 electrons
- Lowered the effect of thermal noise
- Developed by RCA



G.P. Agrawal and N.K. Dutta Semiconductor Lasers

E.g. 45 Mb/s over a distance of 15 km

- Nortel product in 1980.

Changing wavelengths for less noise

Move from 850 nm to 1310 nm window

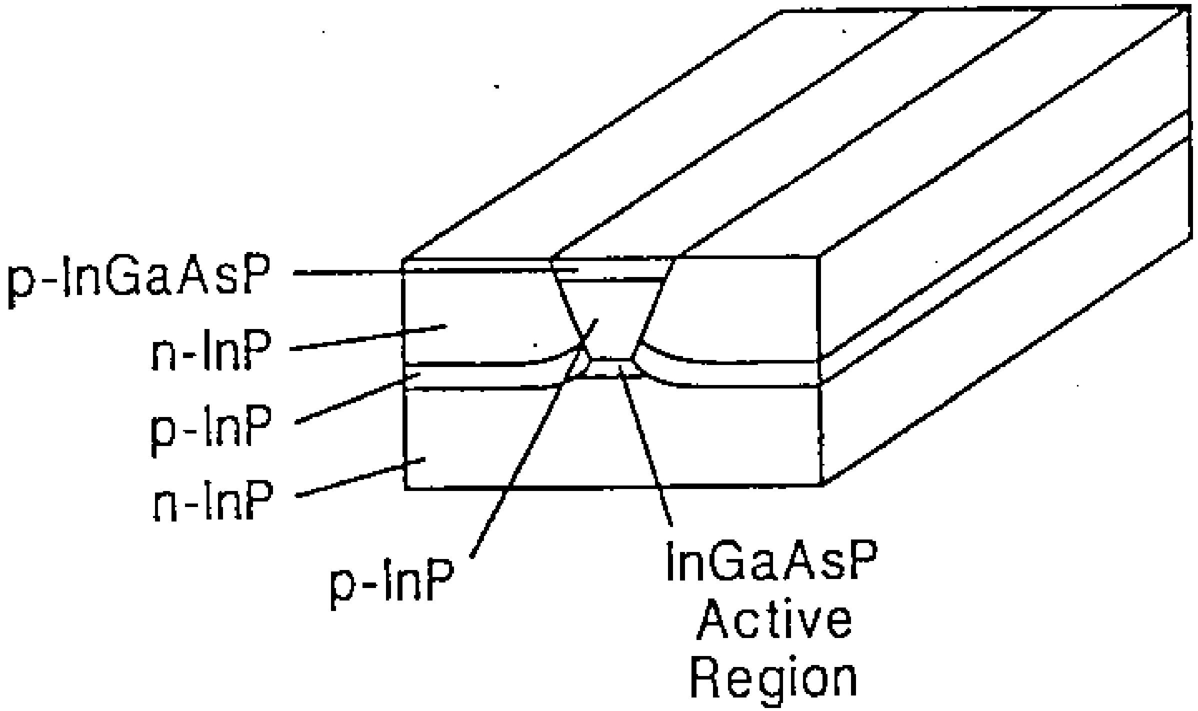
- Fiber loss reduced to 0.4 dB/km
- Improved purity of the glass

1310 nm InGaAsP Fabry-Perot lasers

Germanium Avalanche Photodiodes

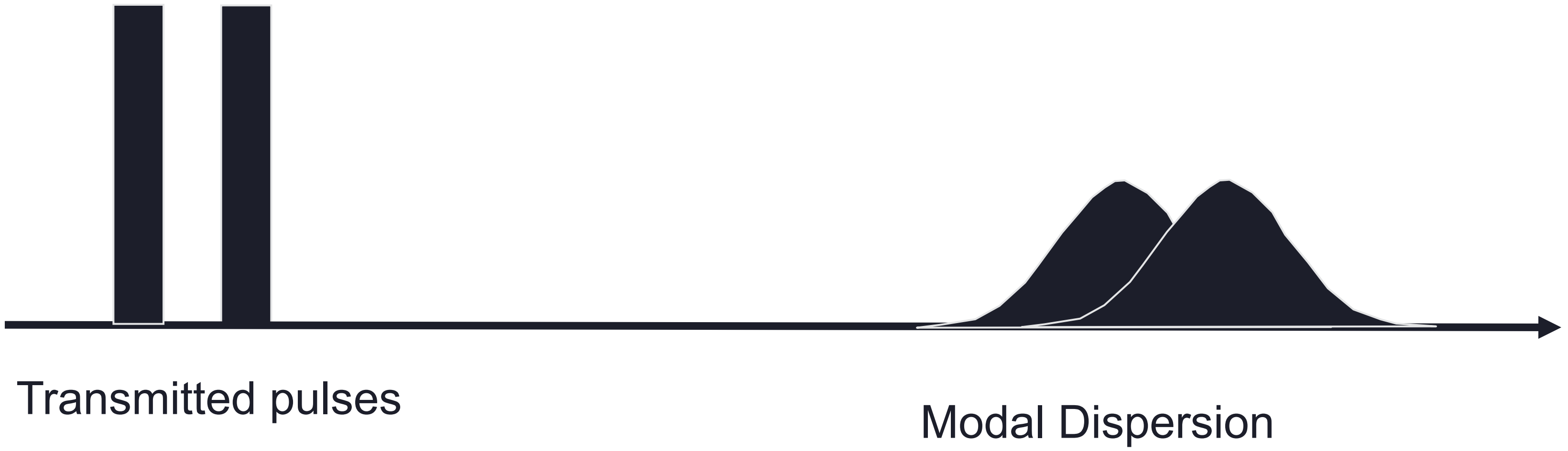
E.g. 45 Mb/s across 45 km

- Nortel product in 1982.

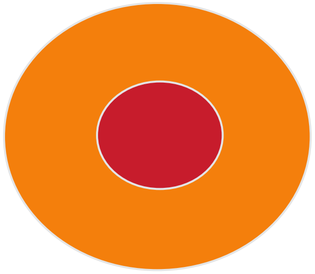


The next barrier: Distortion

Distortion



- 65 micron core fibers support ~250 transmission modes
- Wide variation in propagation velocities across modes
- Coupling between modes due to fiber bends
- Severely limited the bit rates
- E.g. 135 Mb/s across 35 km using duobinary modulation



A new weapon is forged by Corning

Single mode fiber

- 10 micron core diameter

One mode propagates with low loss

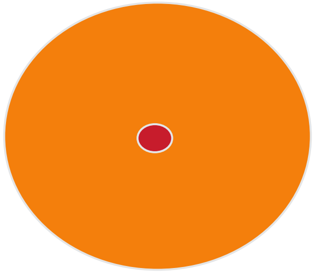
- Two polarizations of that mode
- All other modes attenuated after a few meters

Modal dispersion is eliminated.

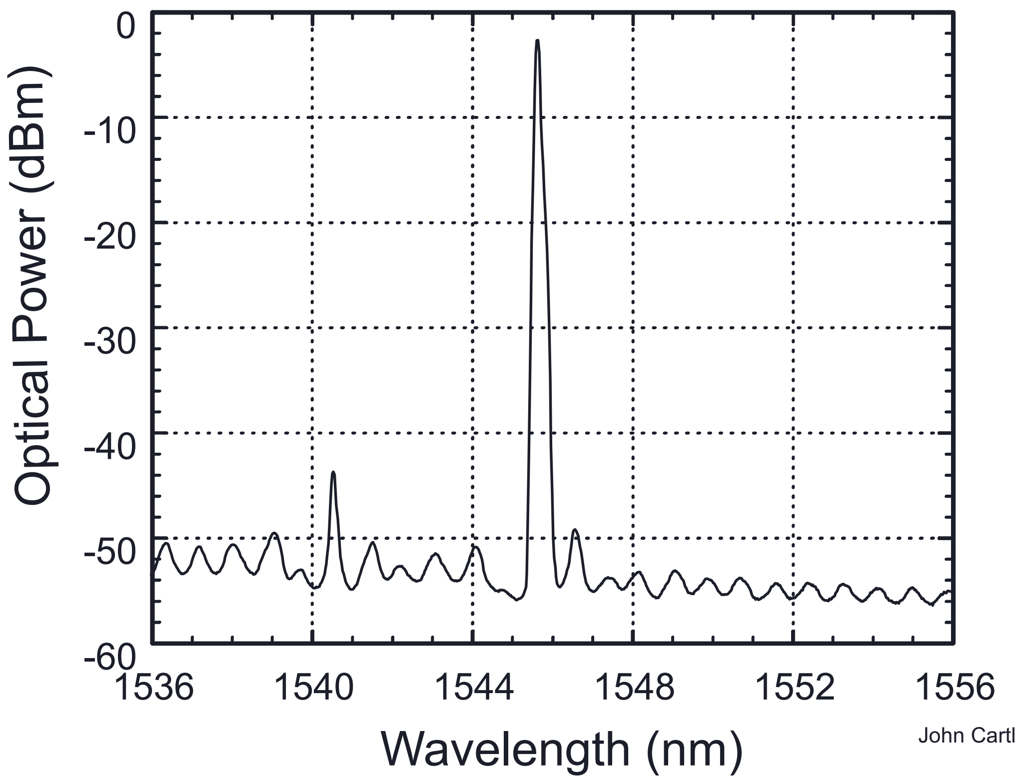
- Major deployment started with MCI in 1982

Allowed up to 565 Mb/s across 40 km

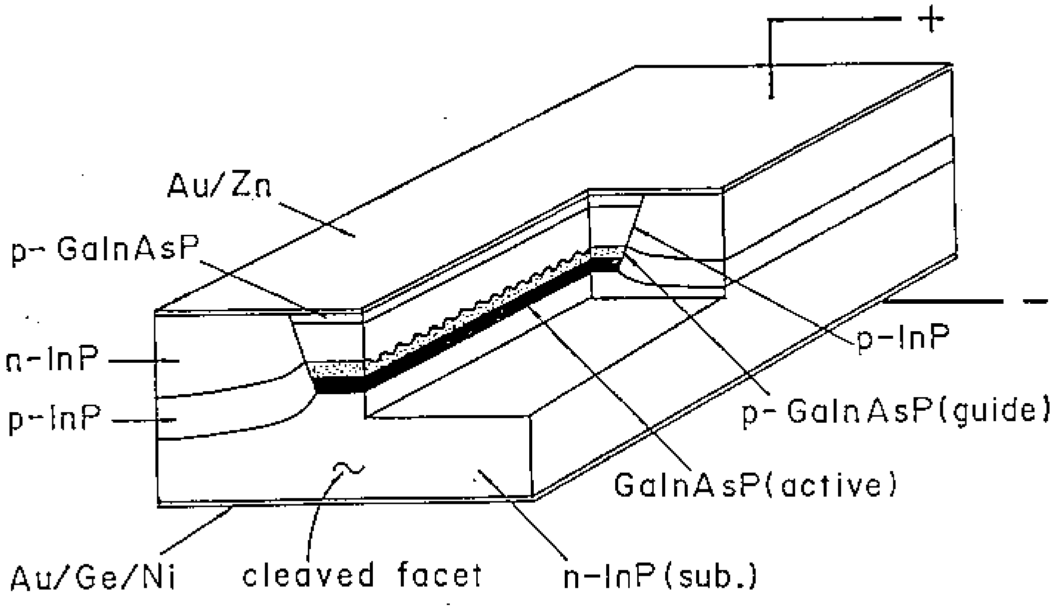
- Nortel product in 1986



Solution: Single Mode Laser

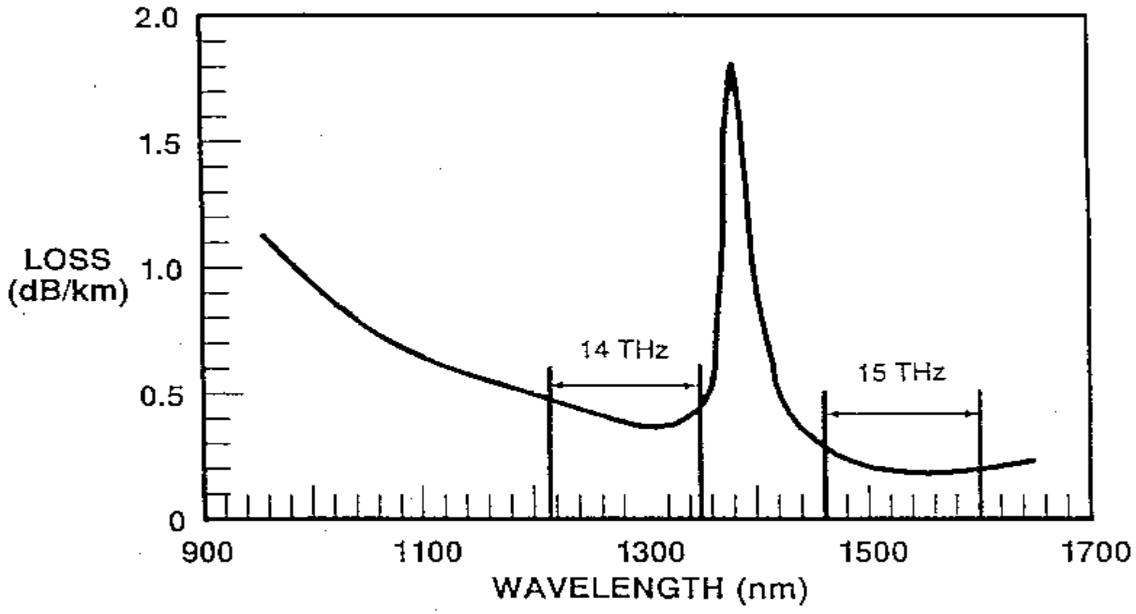


John Cartledge



- Distributed Feedback Lasers only allow one wavelength.
- Eliminated mode partition noise.
- 2.488 Gb/s across 80 km, Nortel product 1990

Change Wavelengths Again, for Less Noise



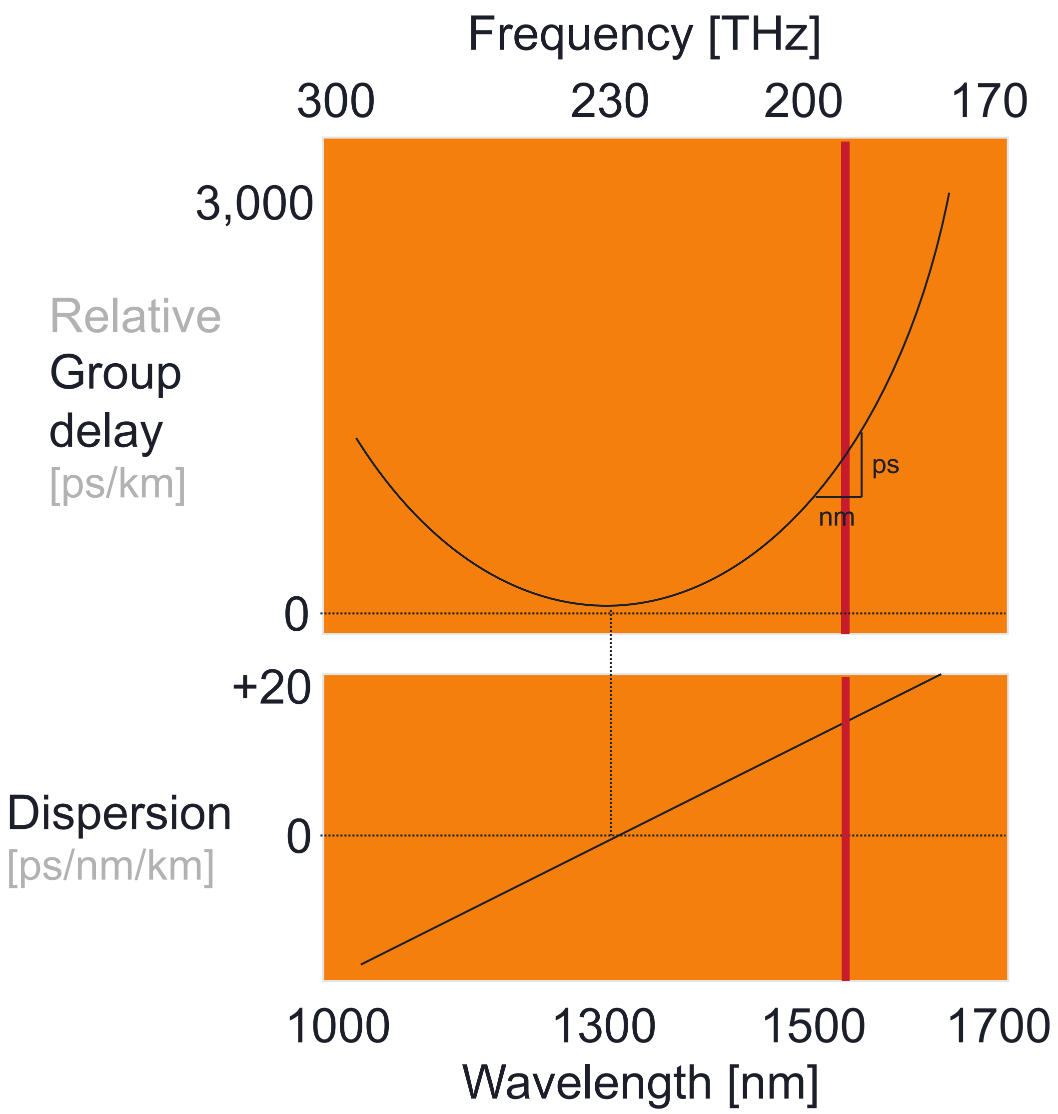
The fiber loss of 0.35 dB/km at 1310 nm limited the spacing between regenerators to about 40 km.

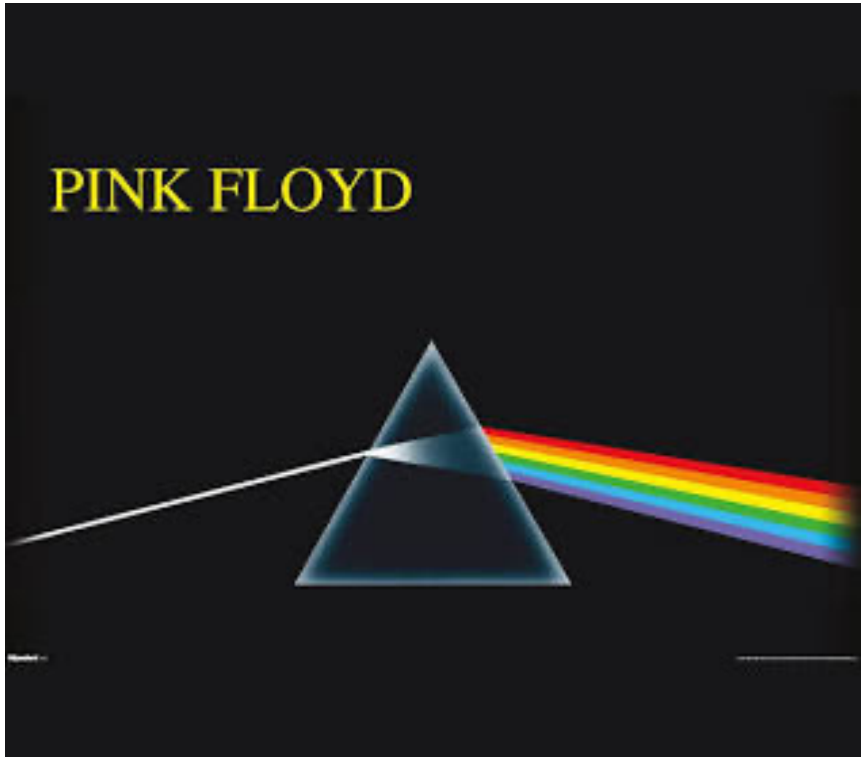
The1550 nm window has loss of 0.2 dB/km

Wavelength Division Multiplexing (WDM)

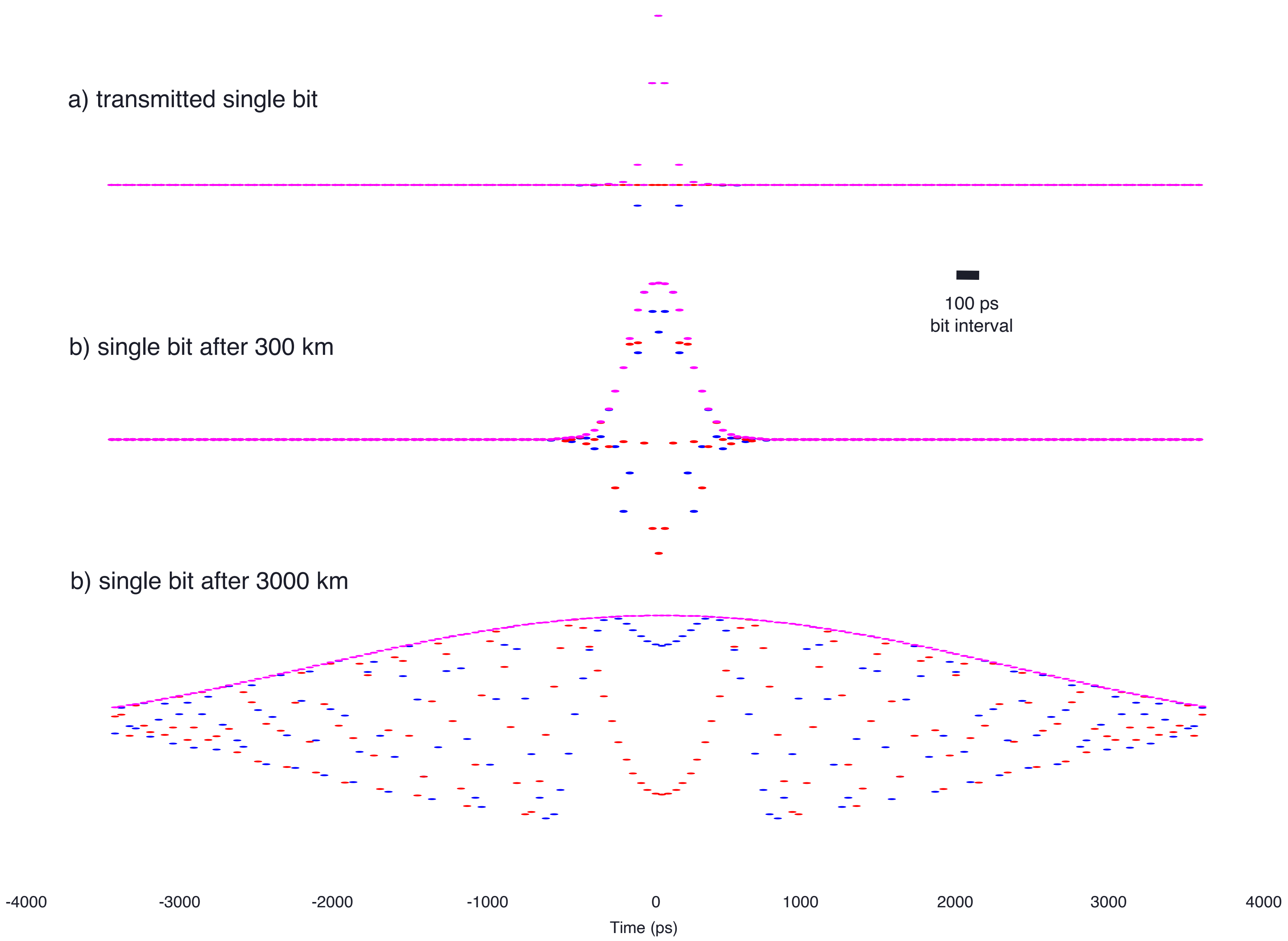
- two wavelengths on one fiber.

Next Barrier: Chromatic Dispersion





Chromatic Dispersion in Optical Fiber

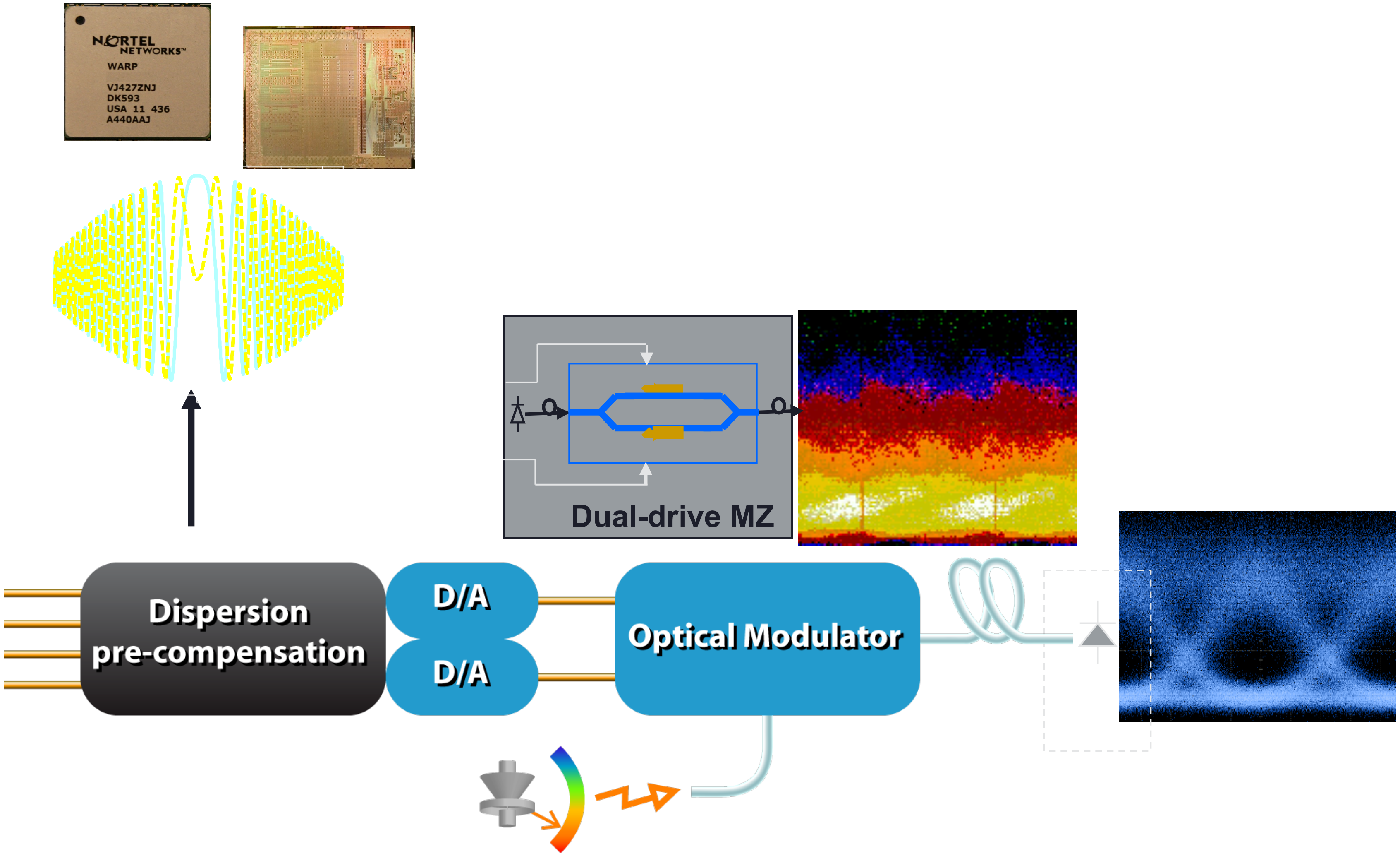


Dispersion Compensation Modules

- Coils of 1 to 20 km of special fiber
- 5 μs to 100 μs of added delay per coil
- $3k to $10k per module

- Each line amp site needs a specific value of optical dispersion compensation engineered for a particular end-to-end connection.
- Cannot simply zero the adjoining dispersion, due to optical nonlinearities.

Complex Plane of E-field



Another breech in the Noise Barrier

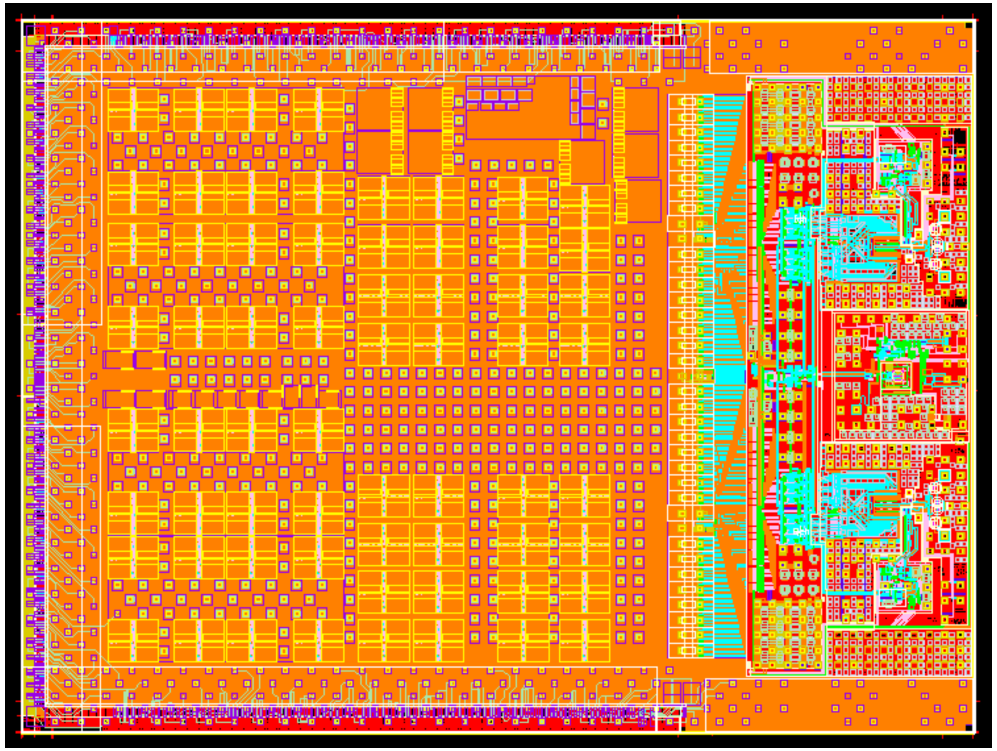
Reach is noise limited to about 80 km

- Cable loss of 0.25 dB/km at 1550 nm

Erbium Doped Fiber Amplifiers are the next weapon

- University of Southhampton
- Coil of ~50 meters of doped fiber, pumped by a laser
- Periodically amplify the optical signal to overcome the effect of loss
- Nortel product 1994

Dispersion Eliminator: WaveLogic-1



0.13 μm BiCMOS

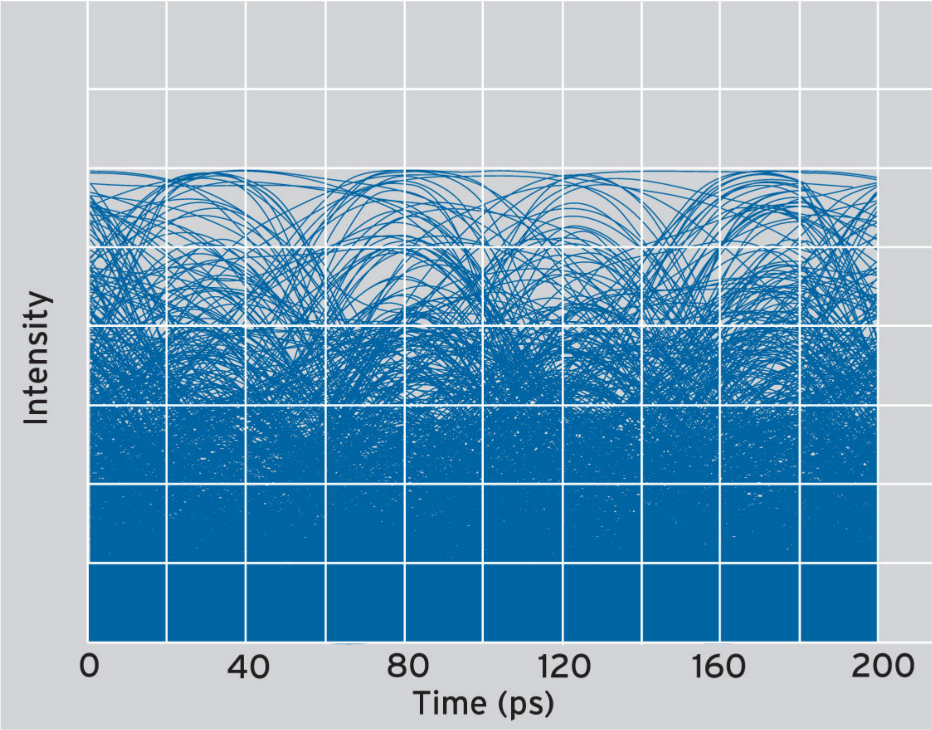
2.5 Mb High Speed Memory

2.0 M Gates

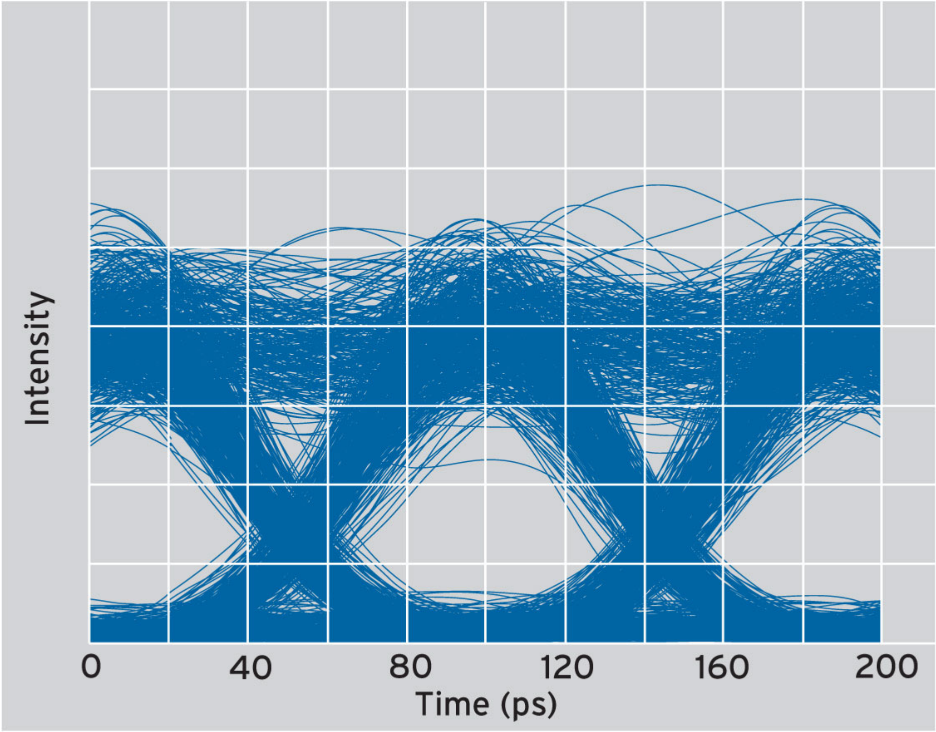
6 T Ops per second

Two 20 Gs/s 6 bit DAC

Dispersion Precompensation

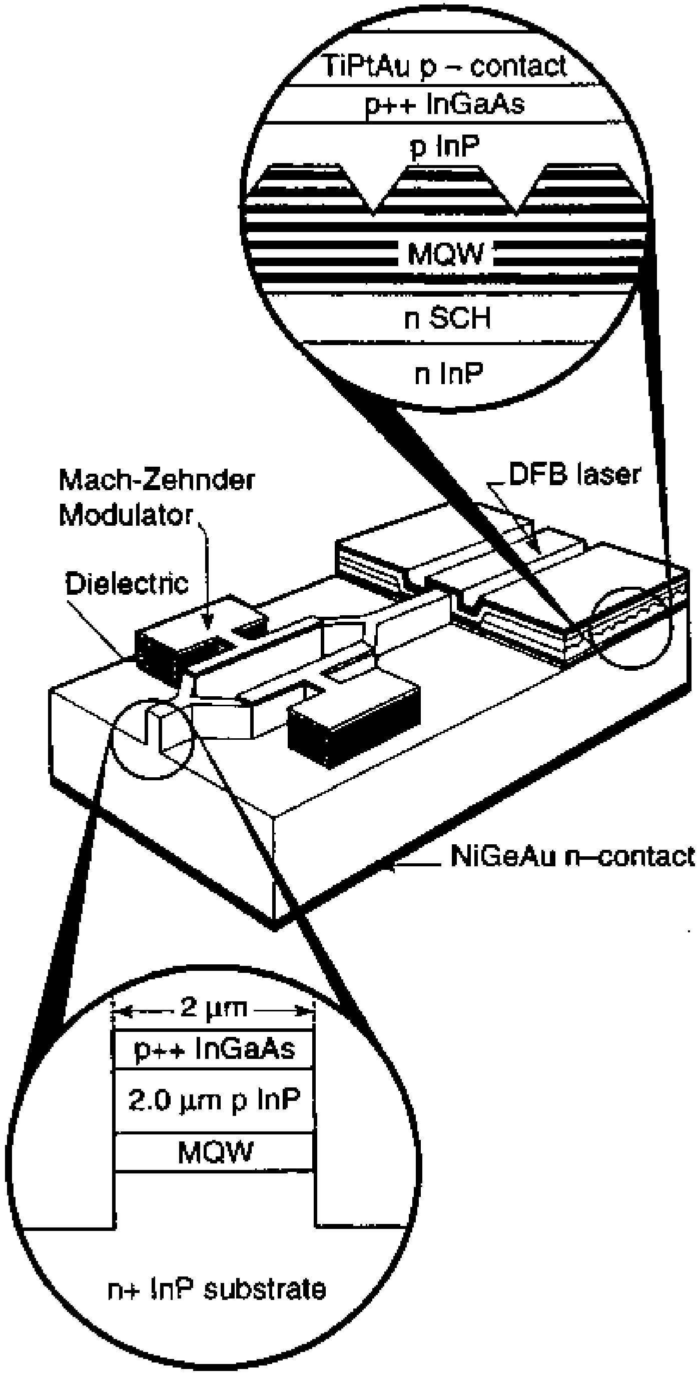


Signal Transmitted



Signal after 1600 km of NDSF
With no optical compensation.

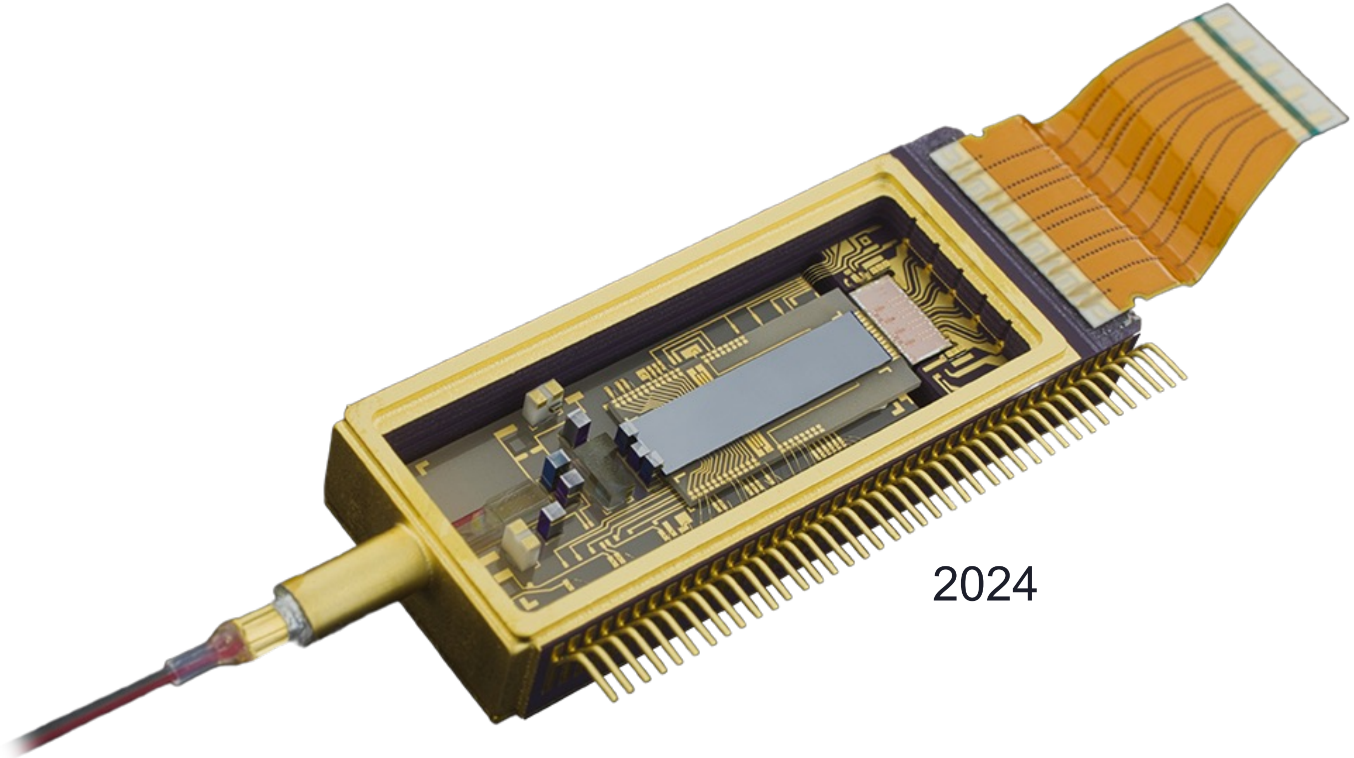
Solution: External Modulators



Controlled chirp

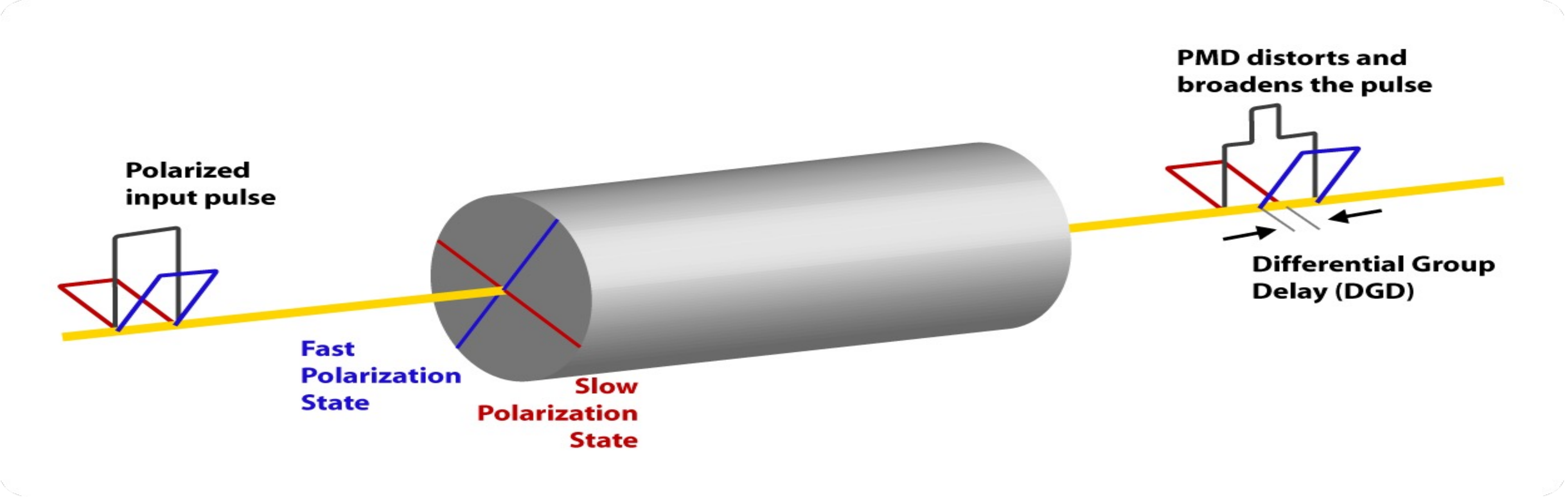
Prevents distortion

Transoceanic distances at 2.4 Gb/s in 1993

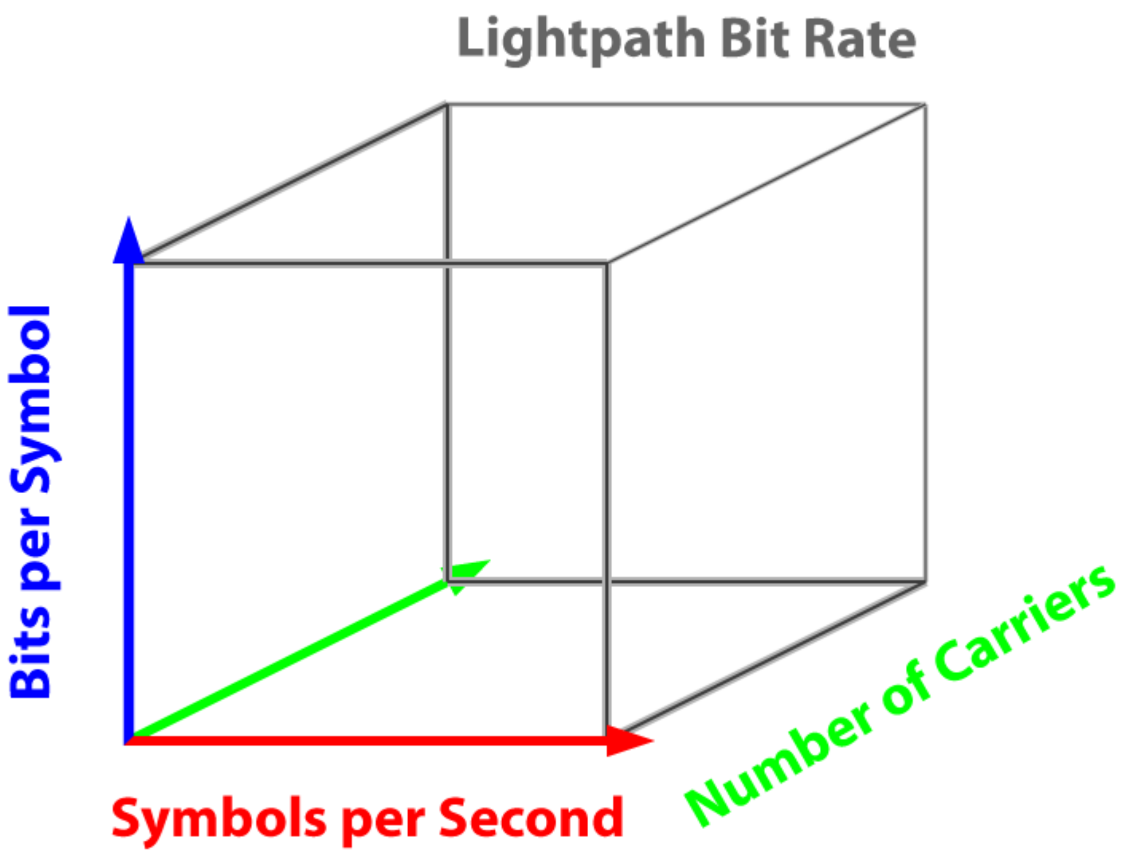


2024

Next Barrier: Polarization Mode Dispersion (PMD)



Lightpath Bit Rate

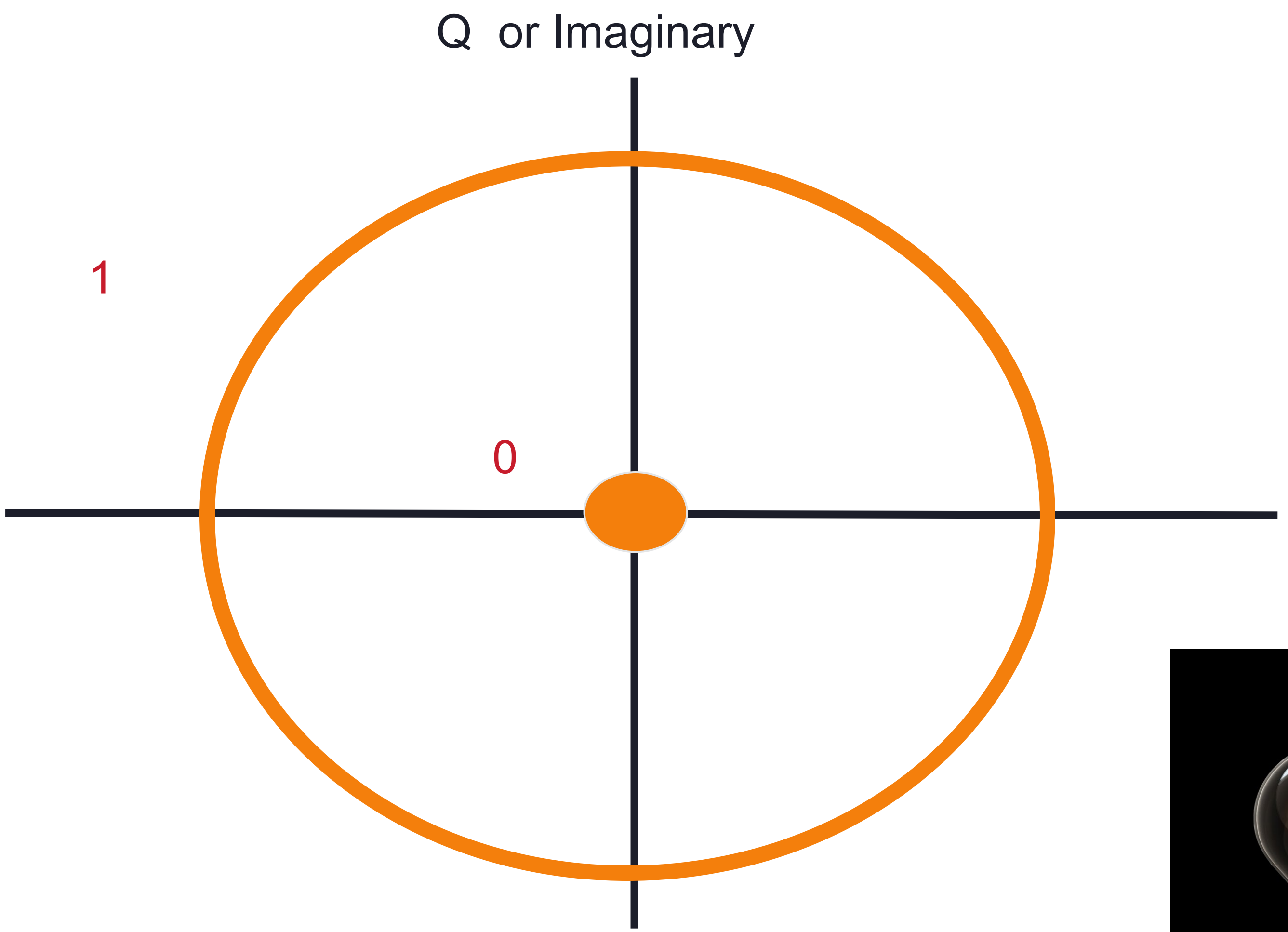


The bit rate is the product of three dimensions

New Assault

Digital Coherent

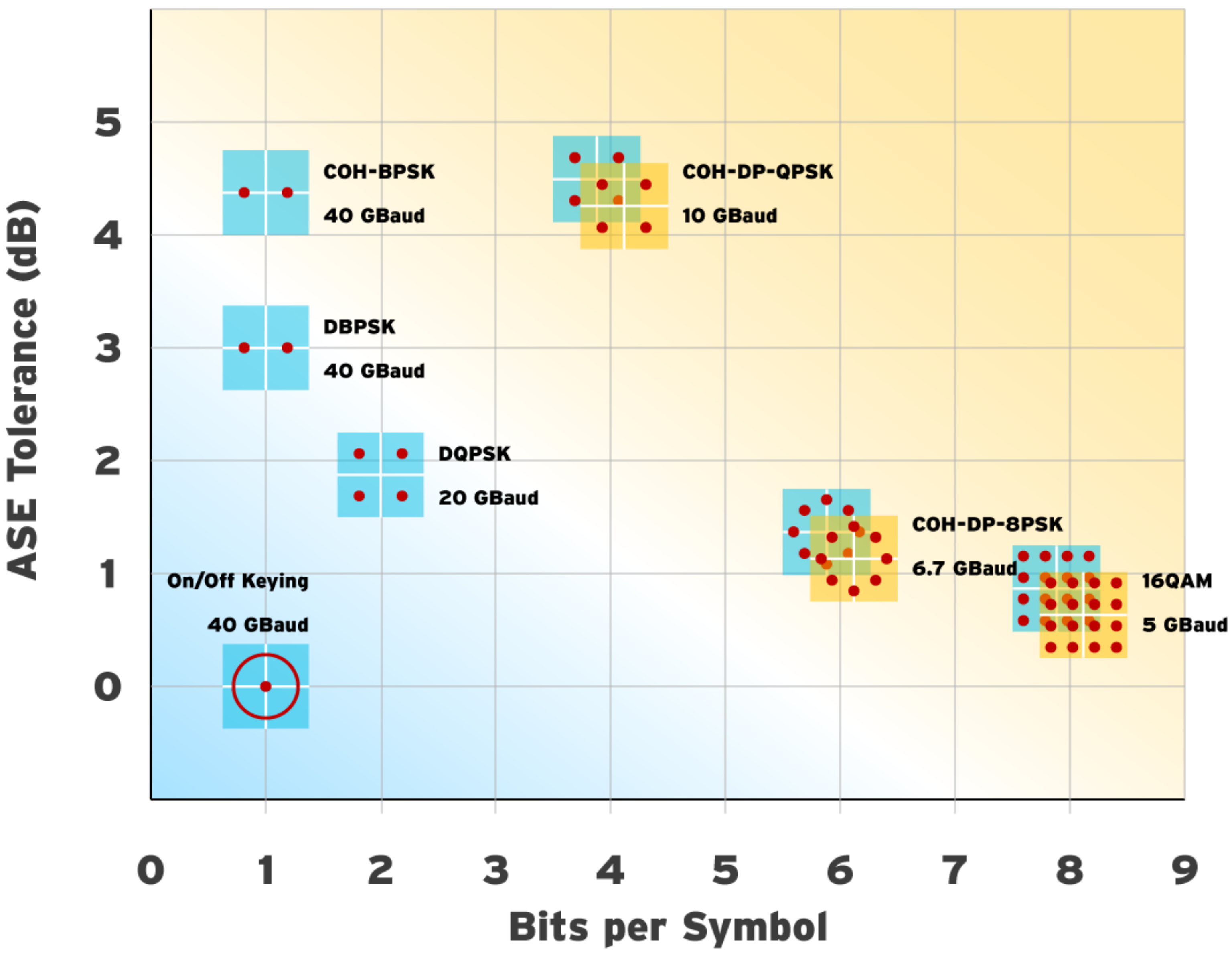
Amplitude Shift Keying (ASK)



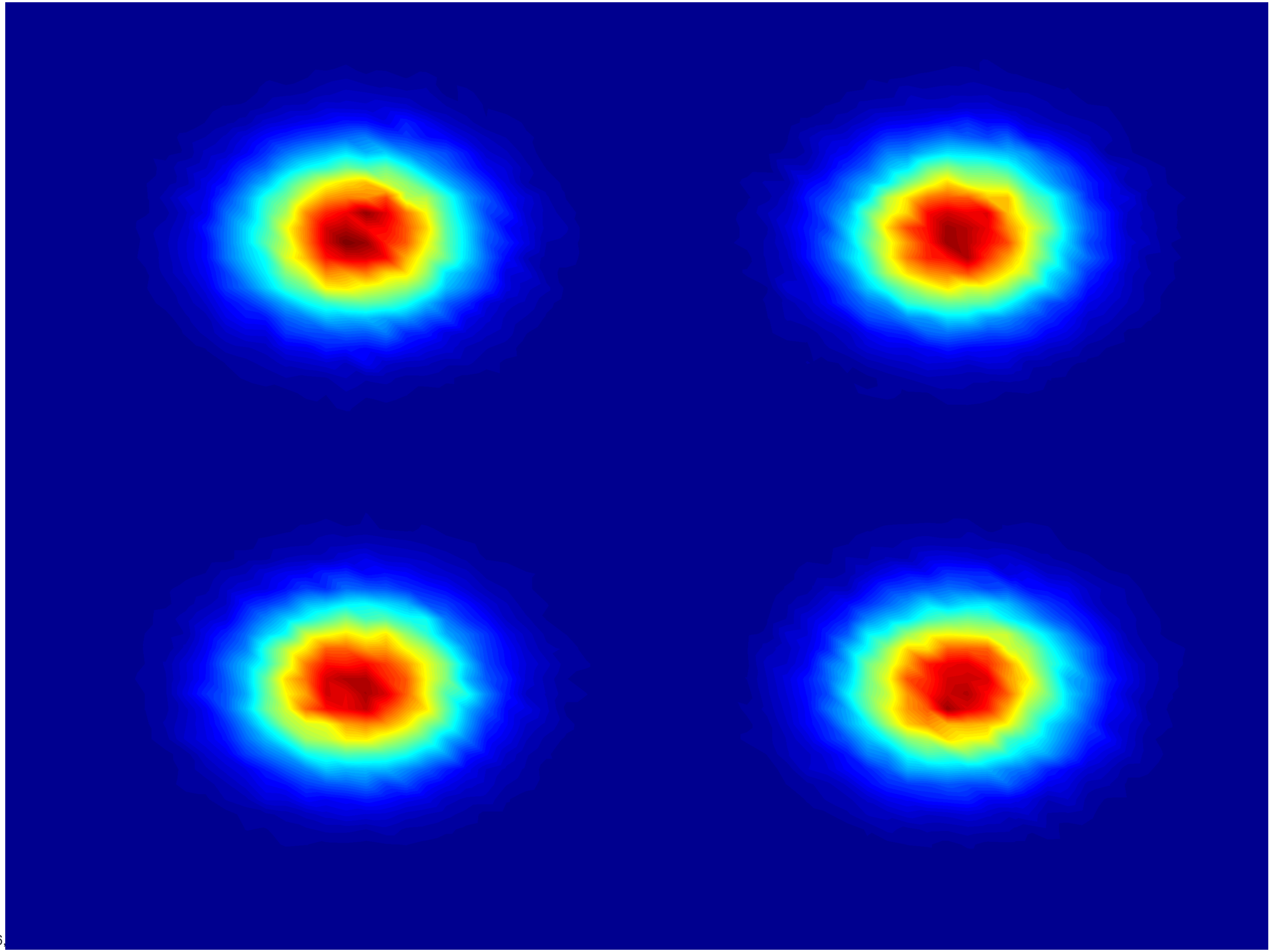
One bit encoded in the amplitude, per symbol

1 bit x 10 Gsymbols/second = 10 Gb/s

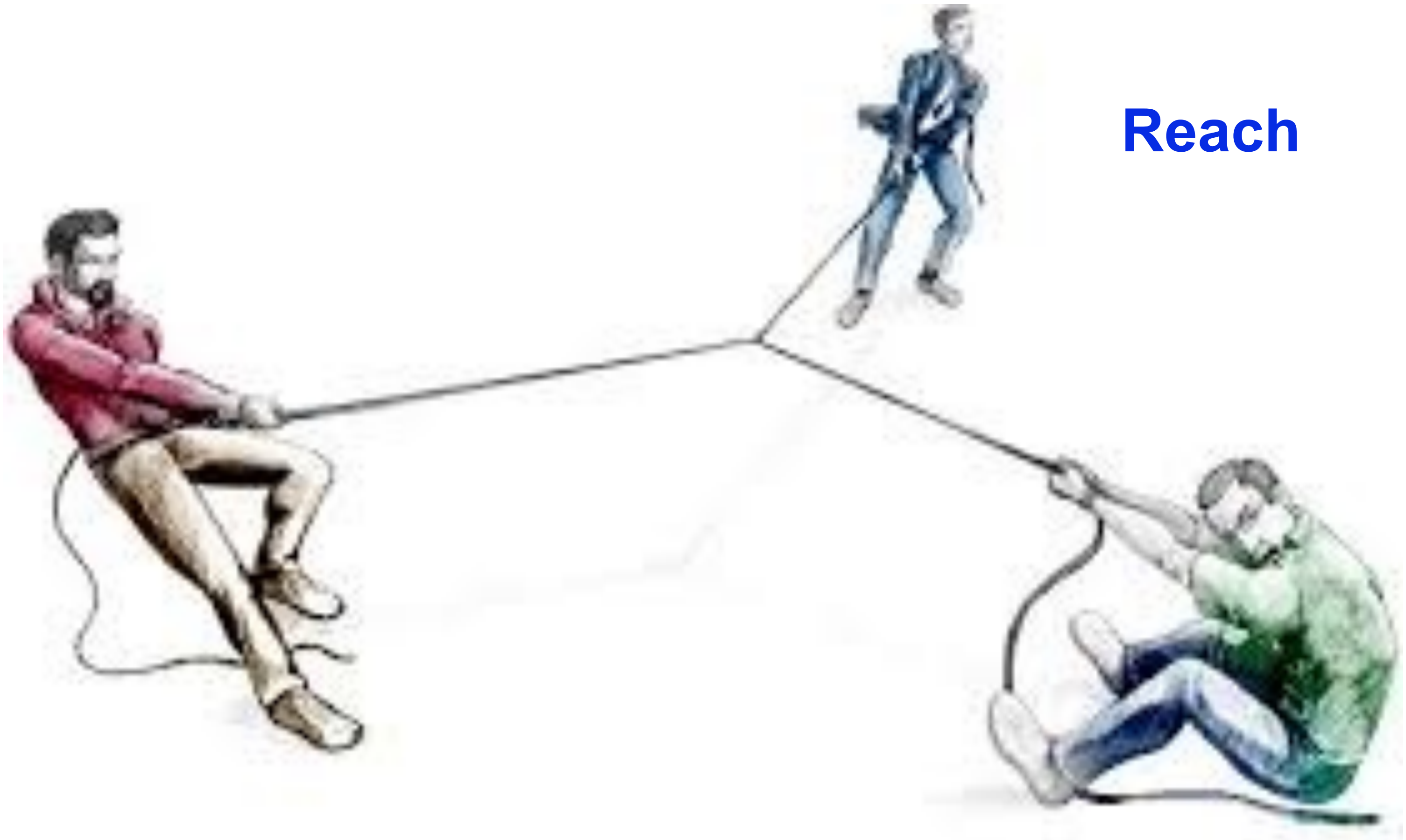
ASE Noise Tolerance for Modulation formats at 40Gb/s



100 Gb/s with QPSK



You Cannot Have Everything at Once!



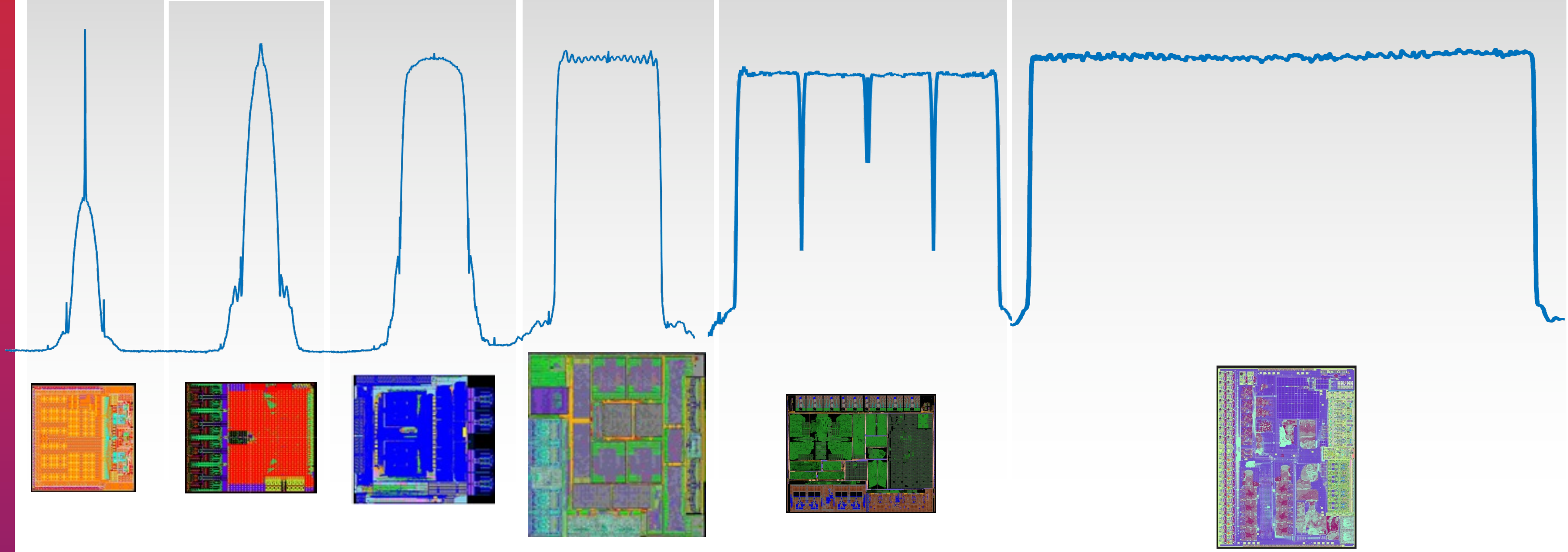
Reach

Low Heat

Spectral Efficiency

Our Family Photo Album

2005 WL1 10G	2008 WL2 40-100G	2012 WL3 50-200G	2017 WLAi 100-400G	2020 WL5 200-800G	2024 WL6 100-1600G



10.7 / 11.1 GBaud	11.5 / 14.6 GBaud	17 / 34.5 GBaud	56.8 GBaud	71.3-106.9 GBaud	67-200 GBaud

WL6e 3nm FinFET CMOS

1 billion gates

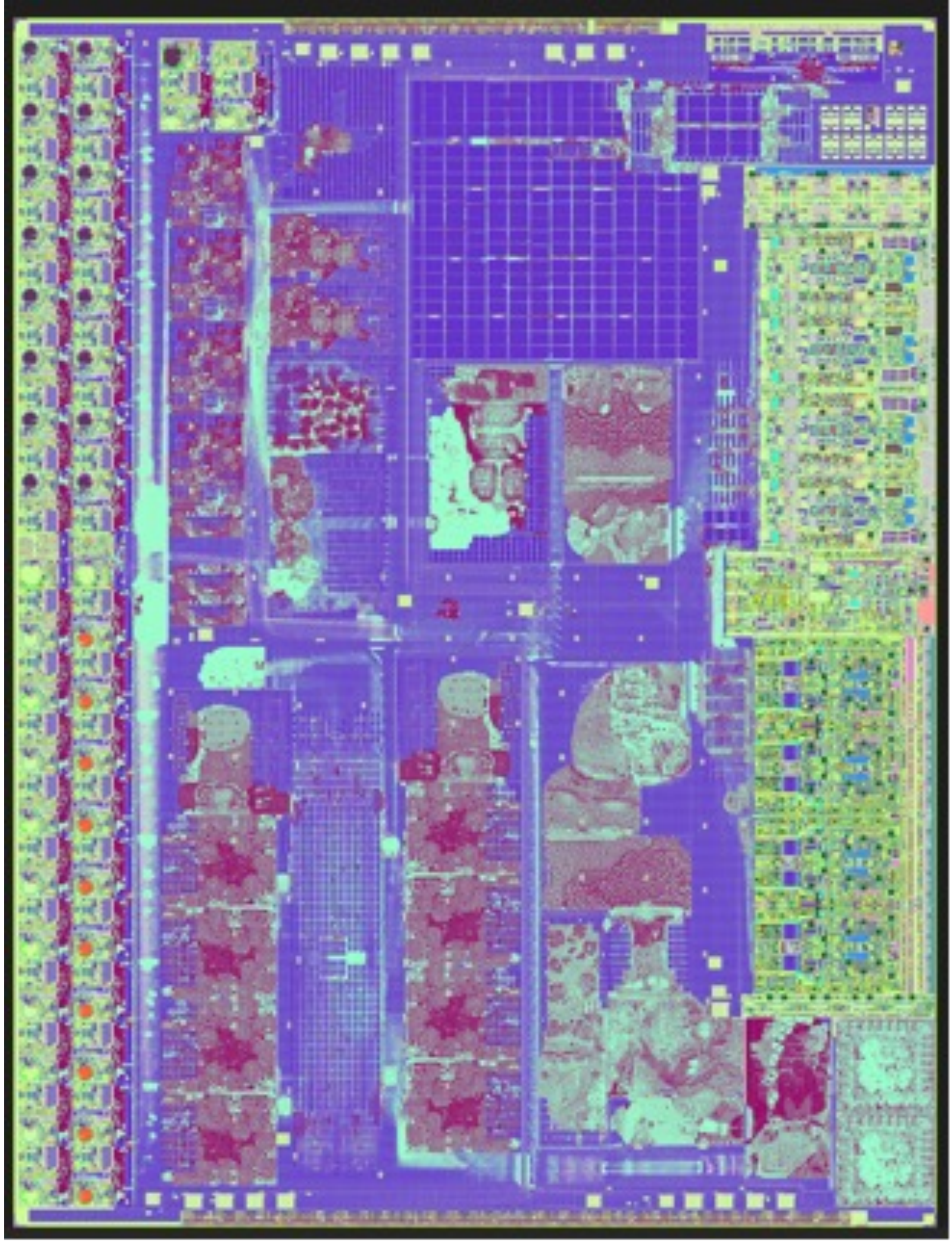
4.16 kilometers of copper wire

1600 T ops

11x15 mm

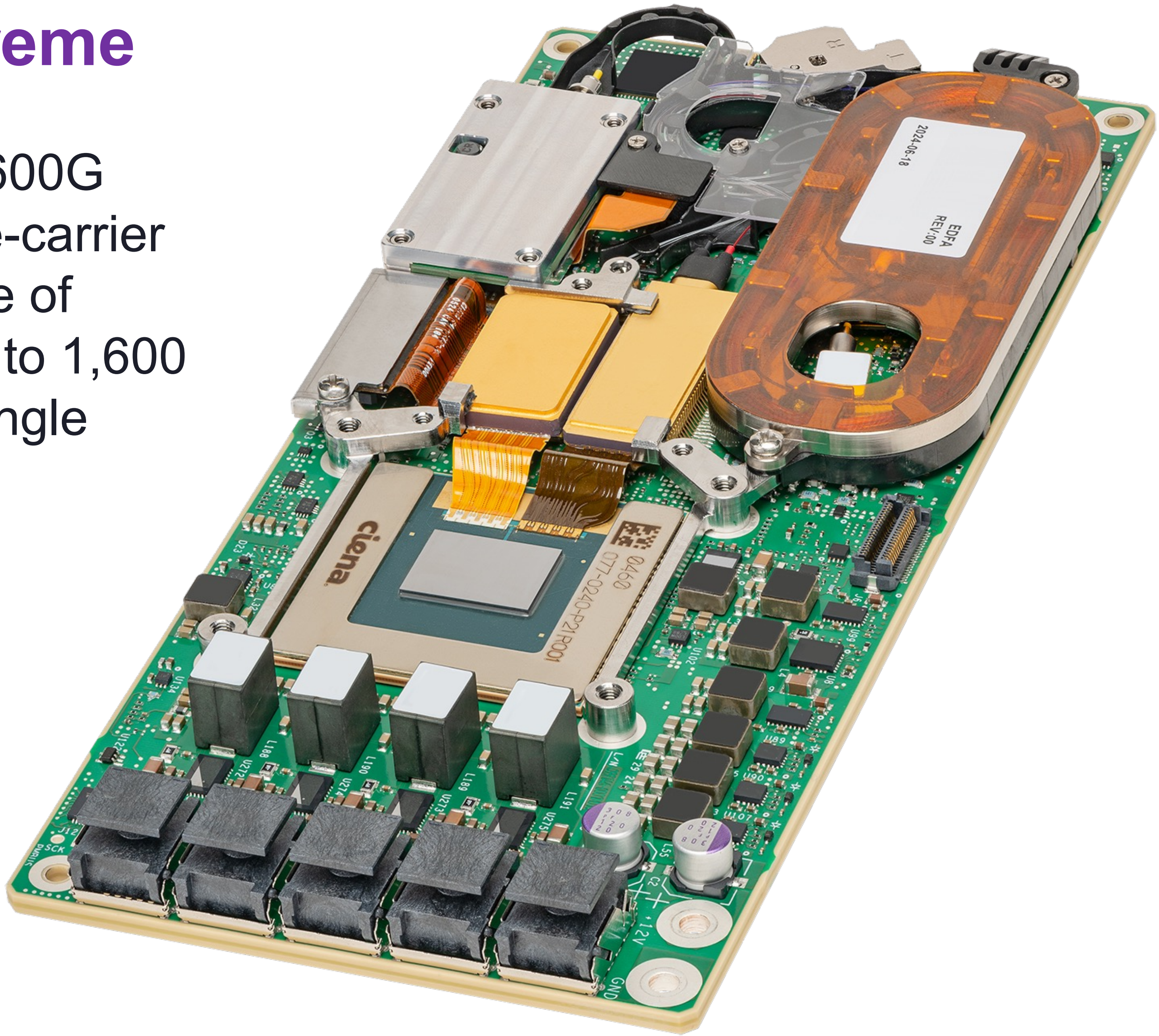
DSP features to mitigate nonlinearities

Ciena product 2024



WaveLogic 6 Extreme

1.6T Transponder Module (1600G Module) is a multi-rate, single-carrier coherent transponder capable of transmitting and receiving up to 1,600 Gb/s of client payload on a single wavelength.



1600 Gb/s

200 GBaud

800 Gb/s Anywhere!

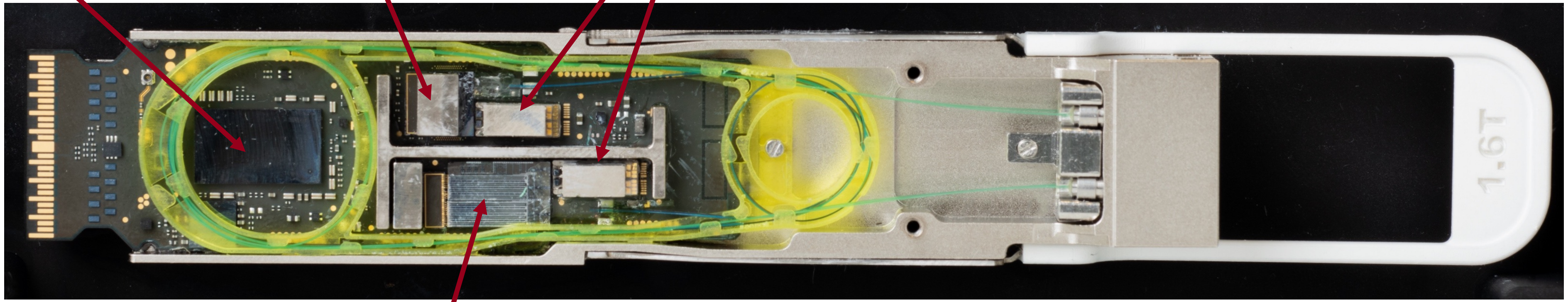
Ciena Product 2024

1.6T Coherent-Lite

3nm ASIC
Coherent
DSP
8x224G
SerDes

Rx PIC

Directly
coupled DFB
lasers



Tx PIC

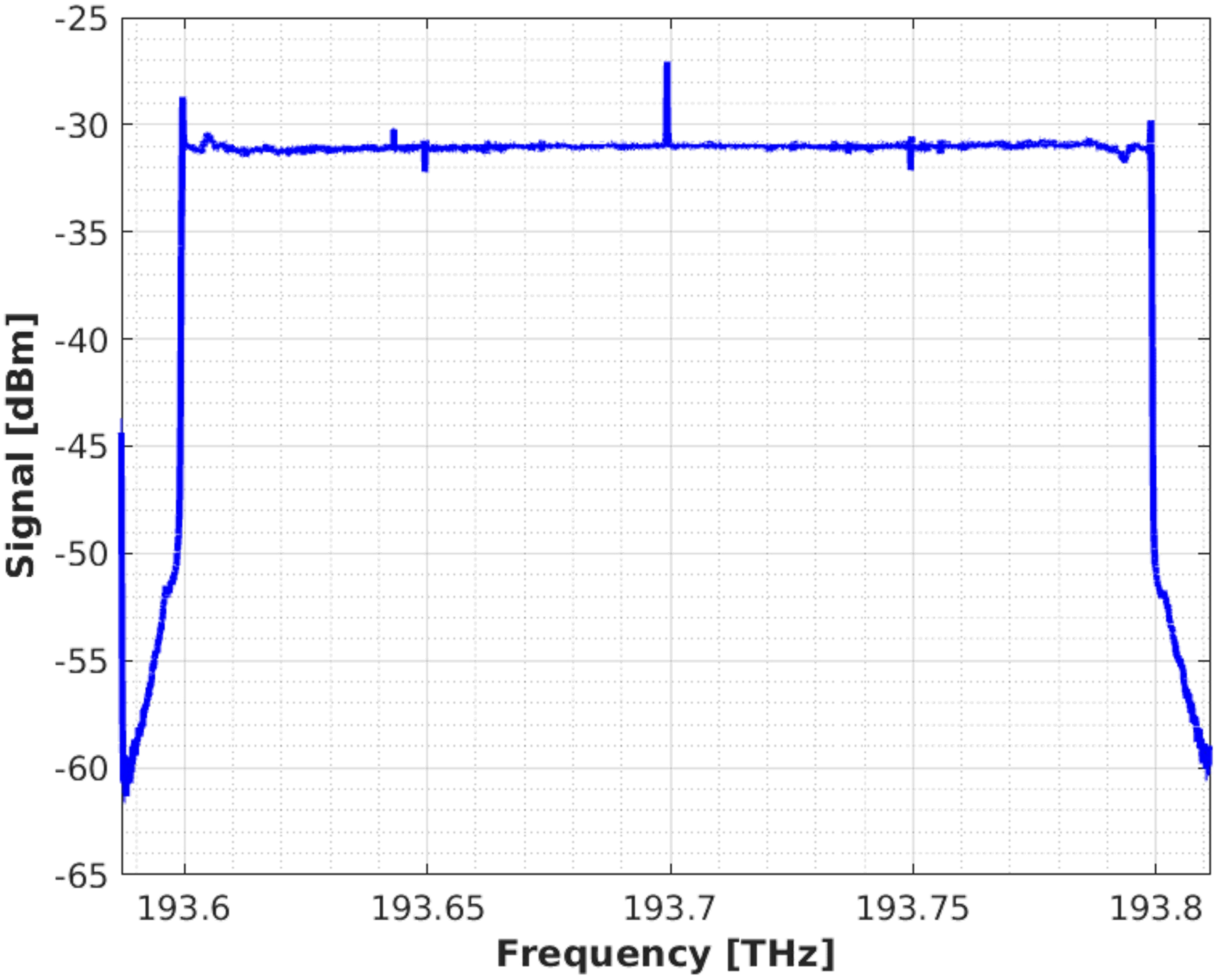
In-service Baud Tuning Demo

Using standard WL6e software, spectral occupancy or Baud can only be set during modem provisioning.

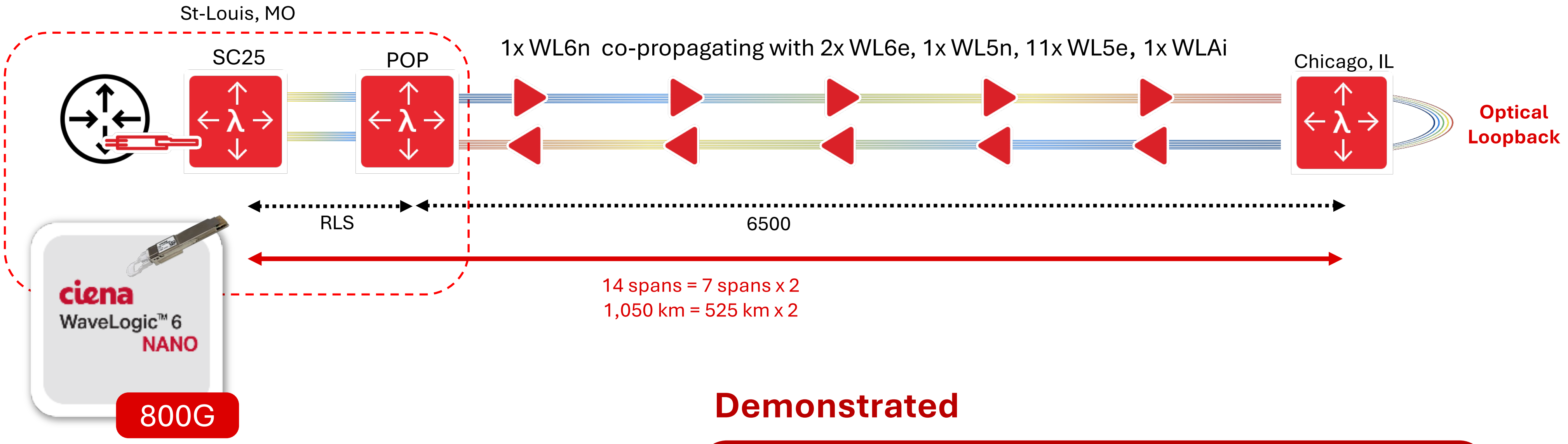
Changing baud after provisioning is a service-impacting process.

However, production hardware with Matlab control:

- **800 Gbit/s of client traffic**
- **Baud tuning from 200-110 Gbaud.**
  - Video of tuning at 0.2%/s; sped up for brevity.
- **NO line FEC hits.**



WL6n 800G Performance Trial



Configuration

	WL6n OSFP-DD
	3rd party 800G switch/router
	6500 and RLS photonics

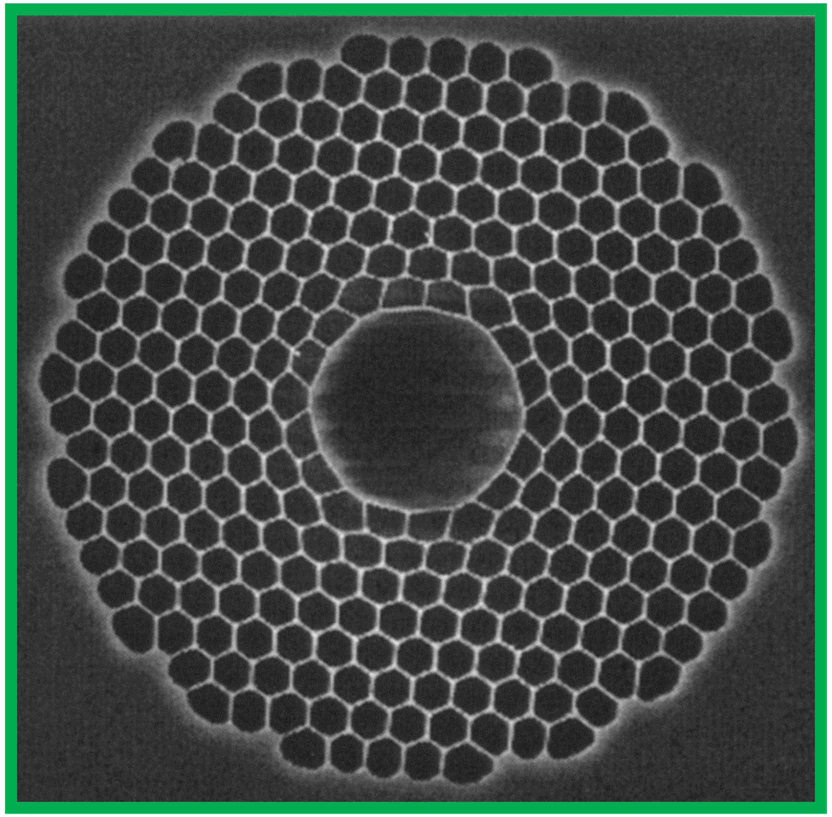
Demonstrated

- ✓ Error-free 800ZR+ performance over **1,050 km**
- ✓ 12.8dB ESNR
- ✓ 3.2dB OSNR margin

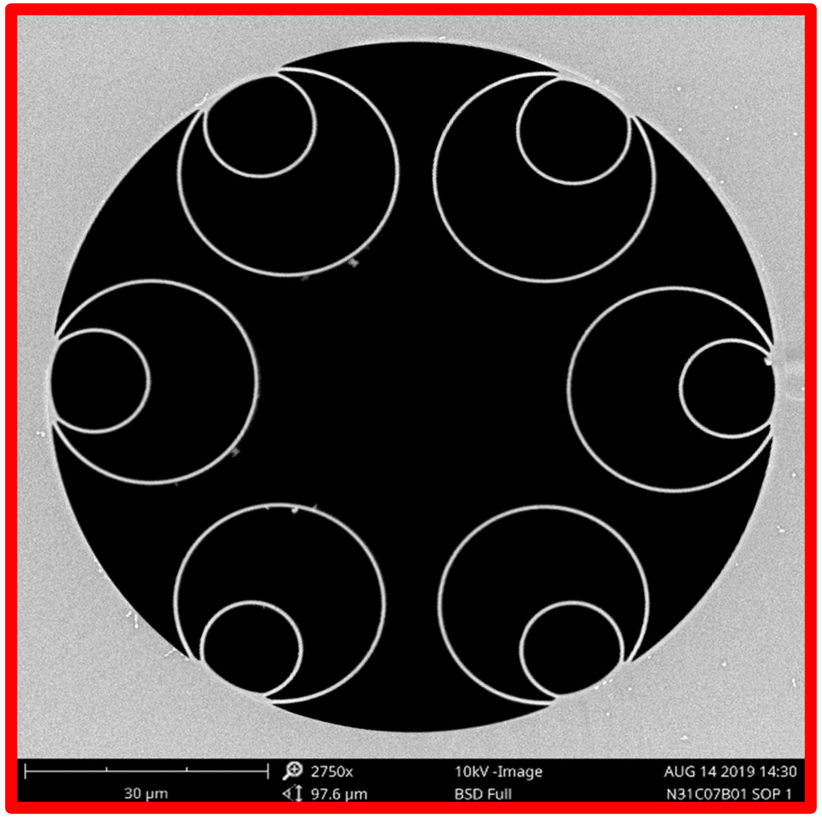
Extrapolation

Sufficient margin identified for **1,800km (24 spans)** at 0 dB margin based on measured, average per-span penalties (NSR_{ASE} and NSR).

Hollow Core Fiber



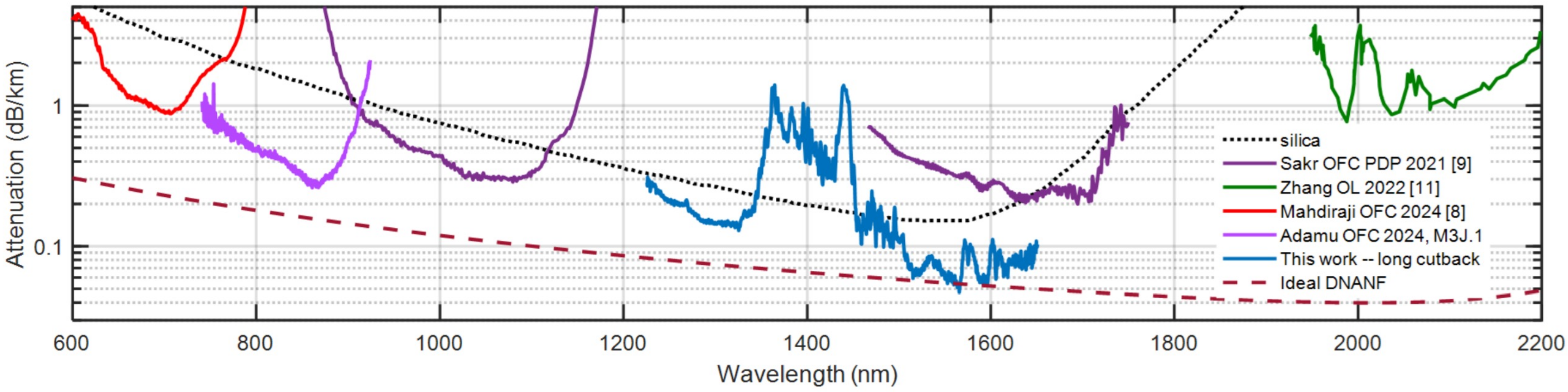
B. Mangan et al., OFC 2004, paper PD24



Bradley et al. ECOC 2019, paper PD3.1

Propagation in vacuum means less latency!

Hollow Core Fiber has Achieved Broad Low Loss



OFC 2024 Th4A.8

Low loss means less noise

Barriers Now Visible on the Horizon

Shannon Limit

Optical Nonlinearities

Heat