Optical Provocations

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BUSINESS MADE SIMPLE

Taxonomy of an Optical Network

> Optical path
  - Fibers, amplifiers, wavelength selective switches

> Modem
  - Communicates a stream of bits

> Control

> Electrical layers 1, 2, etc that use the optical connections
  - Aggregation, interfaces, regeneration, switching, etc

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Outline

> Wavelength Selective Switch; Today

> Barriers to Transmission

> Modems; Today

> Modems; Future

> Optical Switch; Future

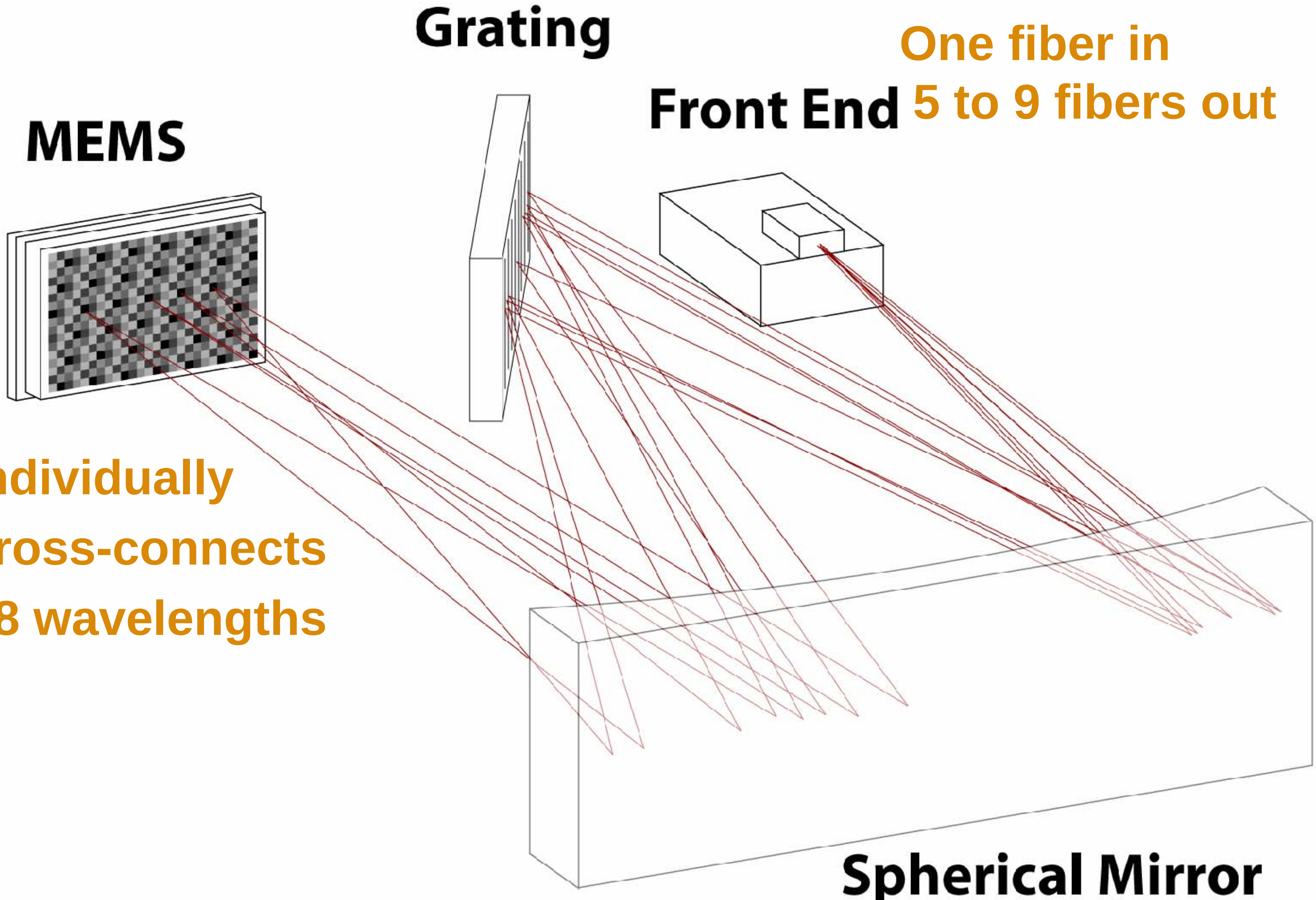
> Speculations on 2010 to 2020

> Research Topics

Wavelength Selective Switch
Today

Wavelength Selective Switch

One fiber in
5 to 9 fibers out

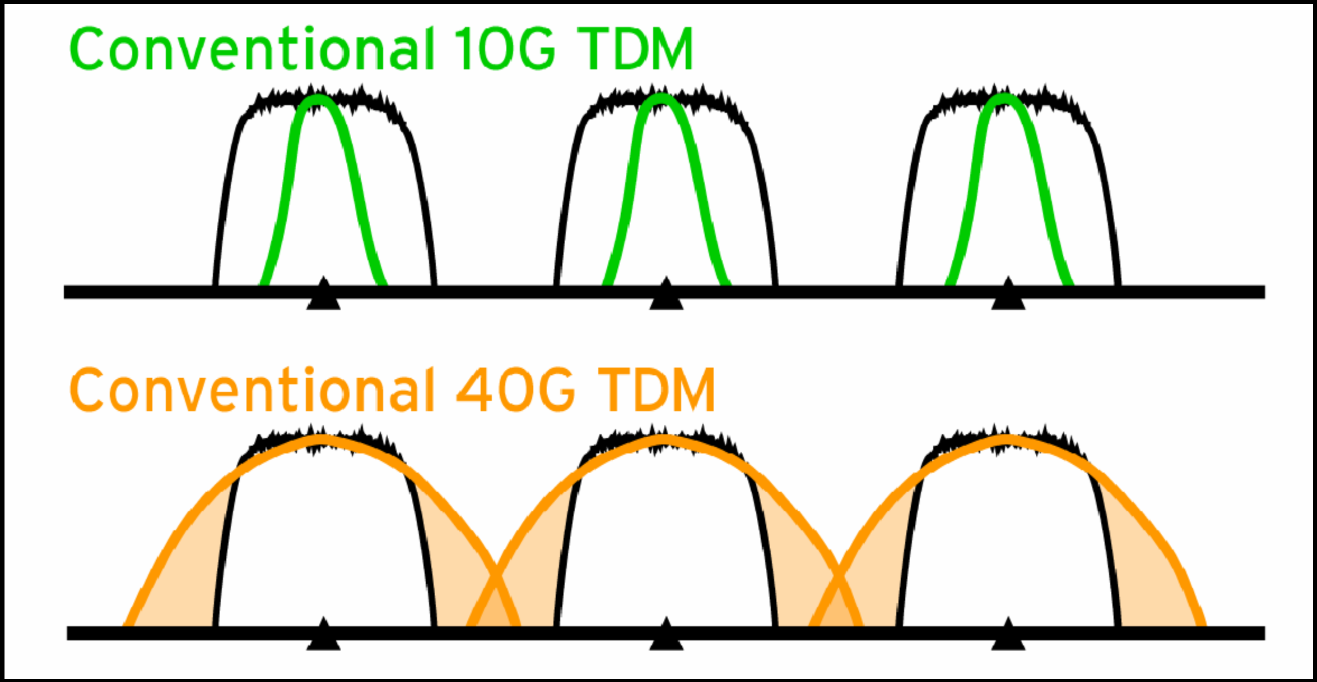


Individually
cross-connects
88 wavelengths

Physical Barriers to High Capacity Transmission

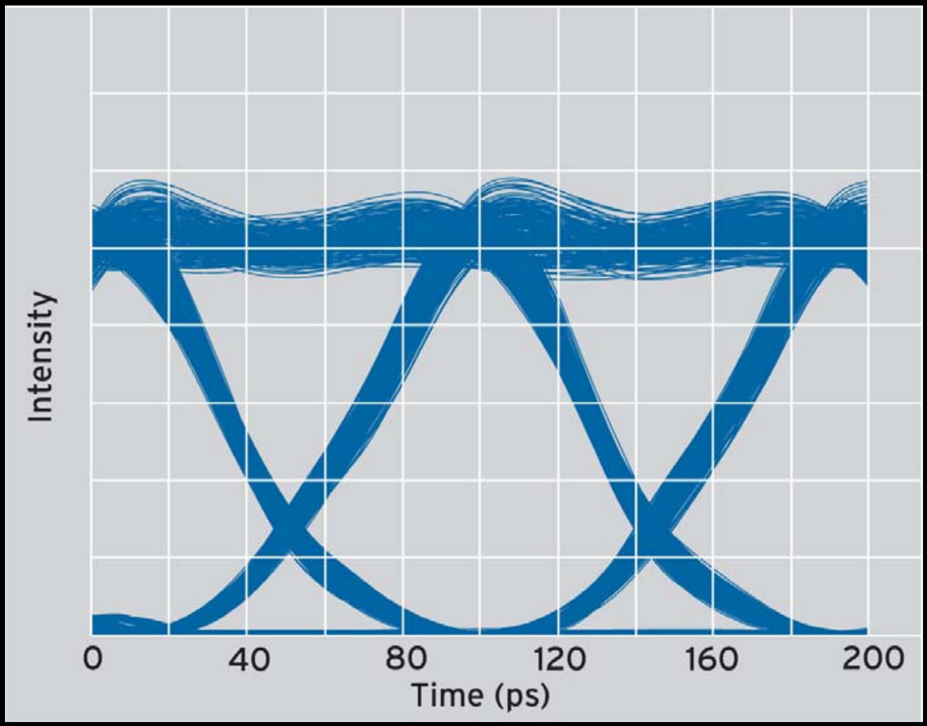
Filter Concatenation

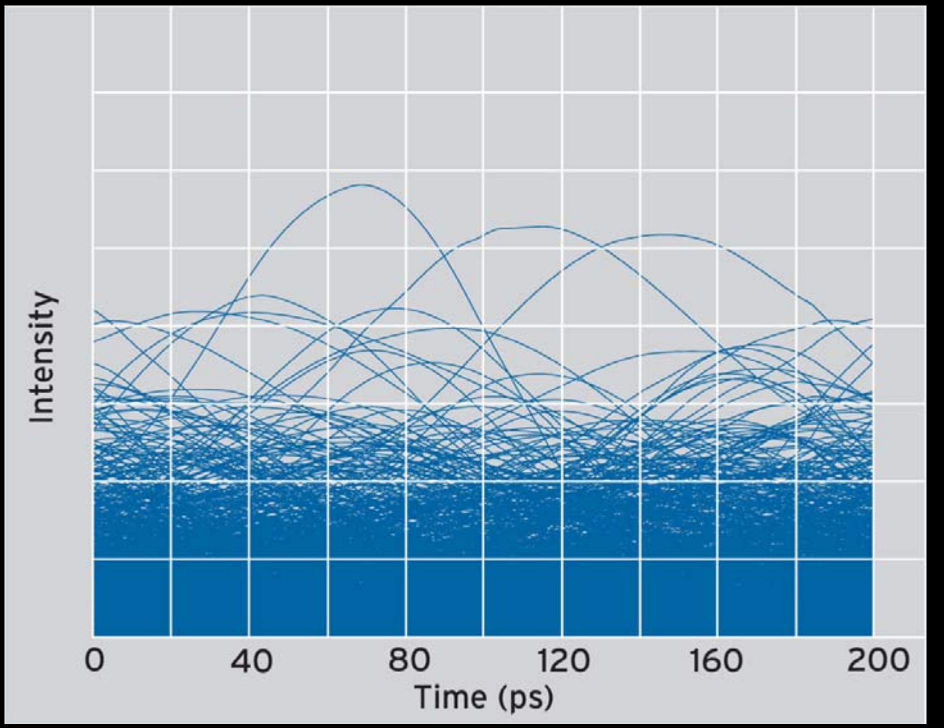
50GHz Wavelength Selective Switch (WSS)



Conventional 40G TDM impacted severely by 50GHz filter concatenation

Effect of Dispersion

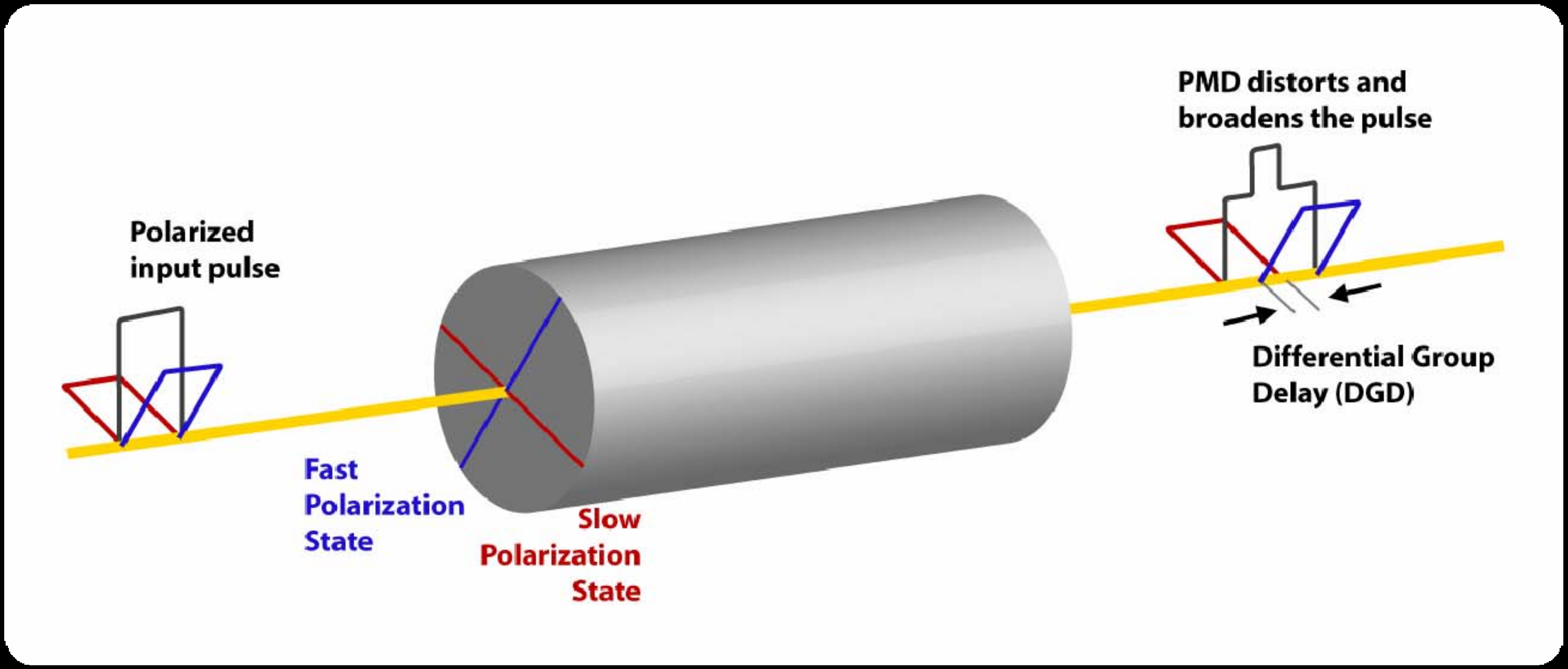




Transmitted Signal

Signal after Dispersion

Polarization Mode Dispersion (PMD)



Noise

10 to 40 to 100 G Symbols per second

> bit interval reduces 100→25→10 ps

> electrical bandwidth increases 10→40→100 GHz

> optical spectrum spreads 0.1→0.8→2 nm (RZ)

> tolerance to dispersion divided by 1→16→100

> tolerance to PMD divided by 1→4→10

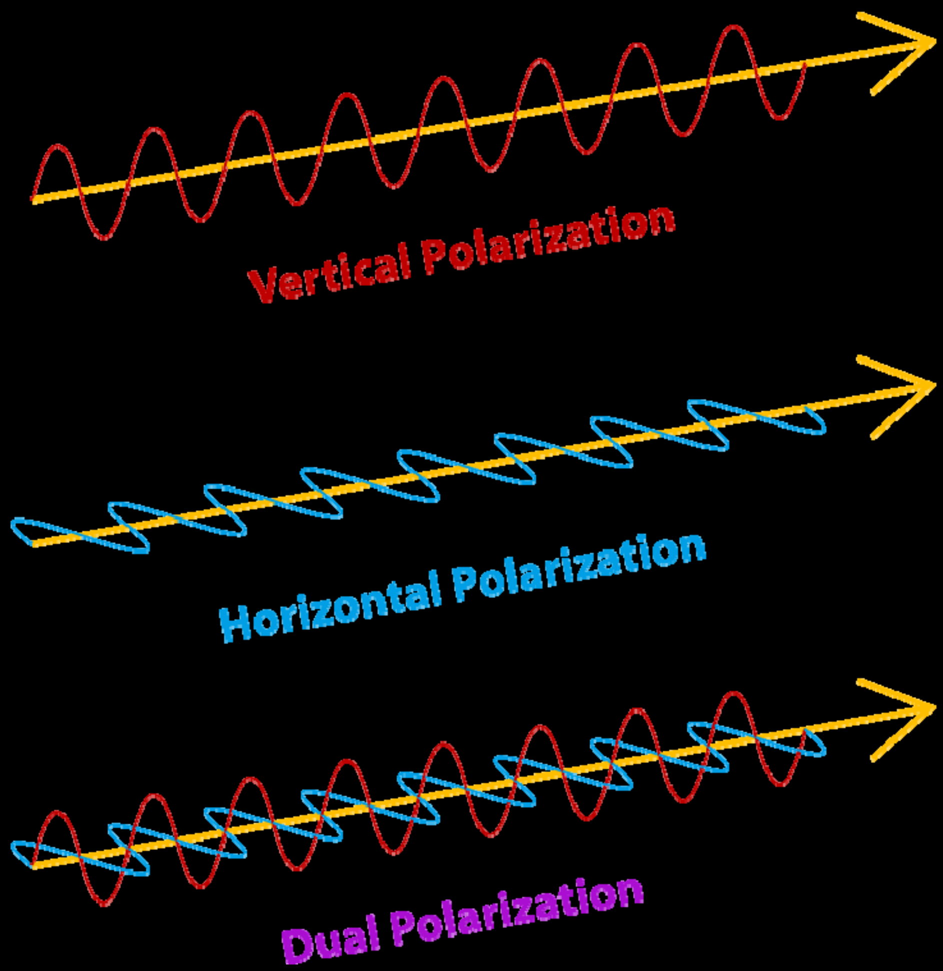
> rise-times sharpen, causing optical nonlinearities

> 6 dB loss in noise margin = ¼ of the reach at 40G

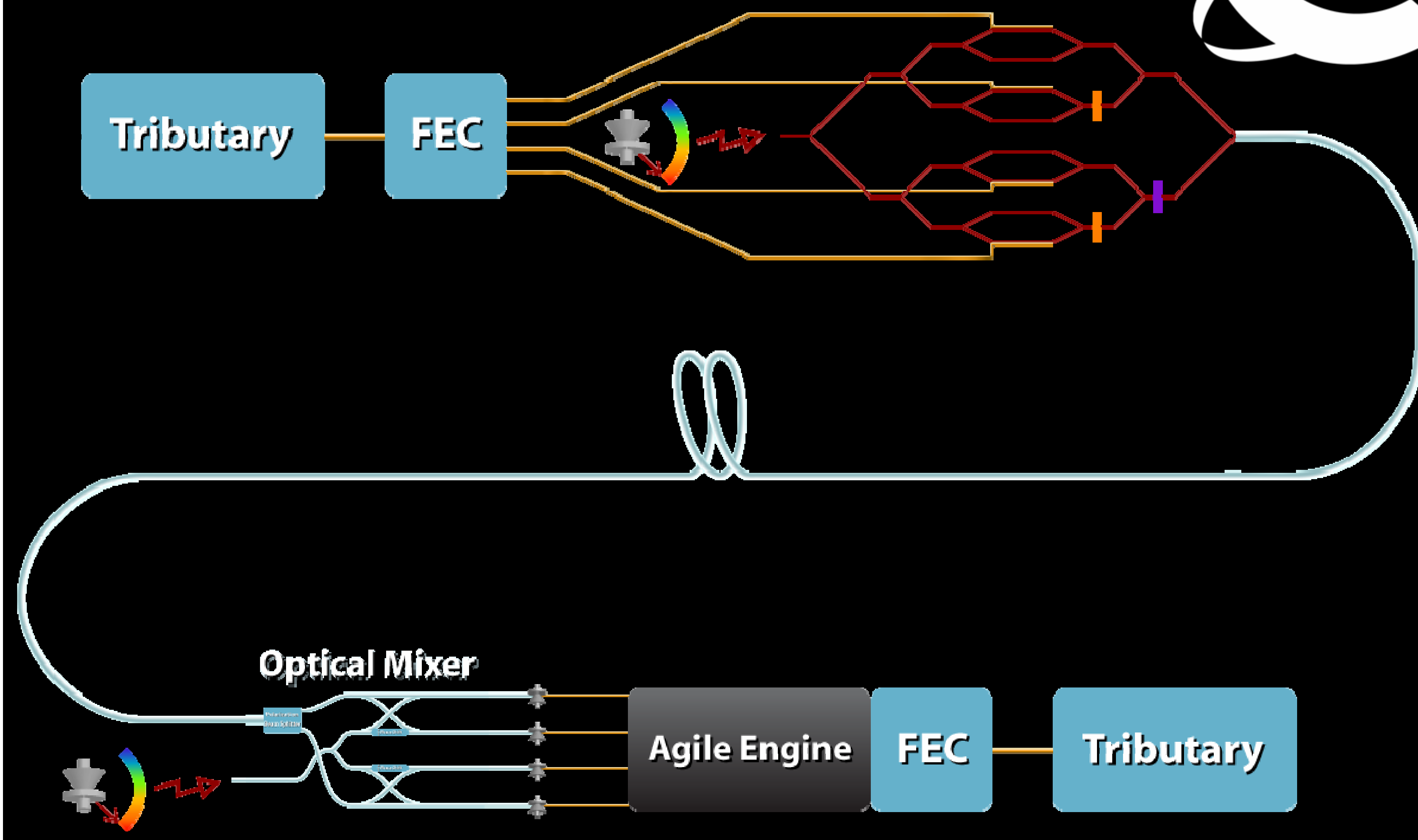
> 10 dB loss in noise margin = 1/10 of the reach at 100G

Modems

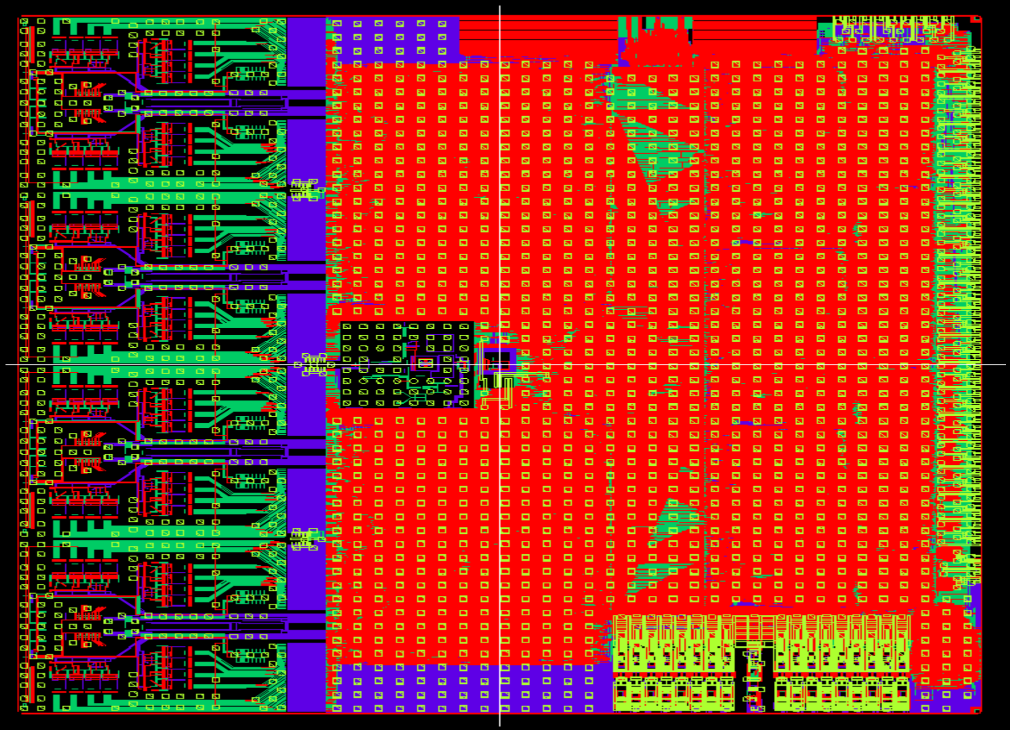
Dual Polarization



Coherent Modem



Coherent Receiver: CMOS ASIC



90 nm CMOS

20 M Gates

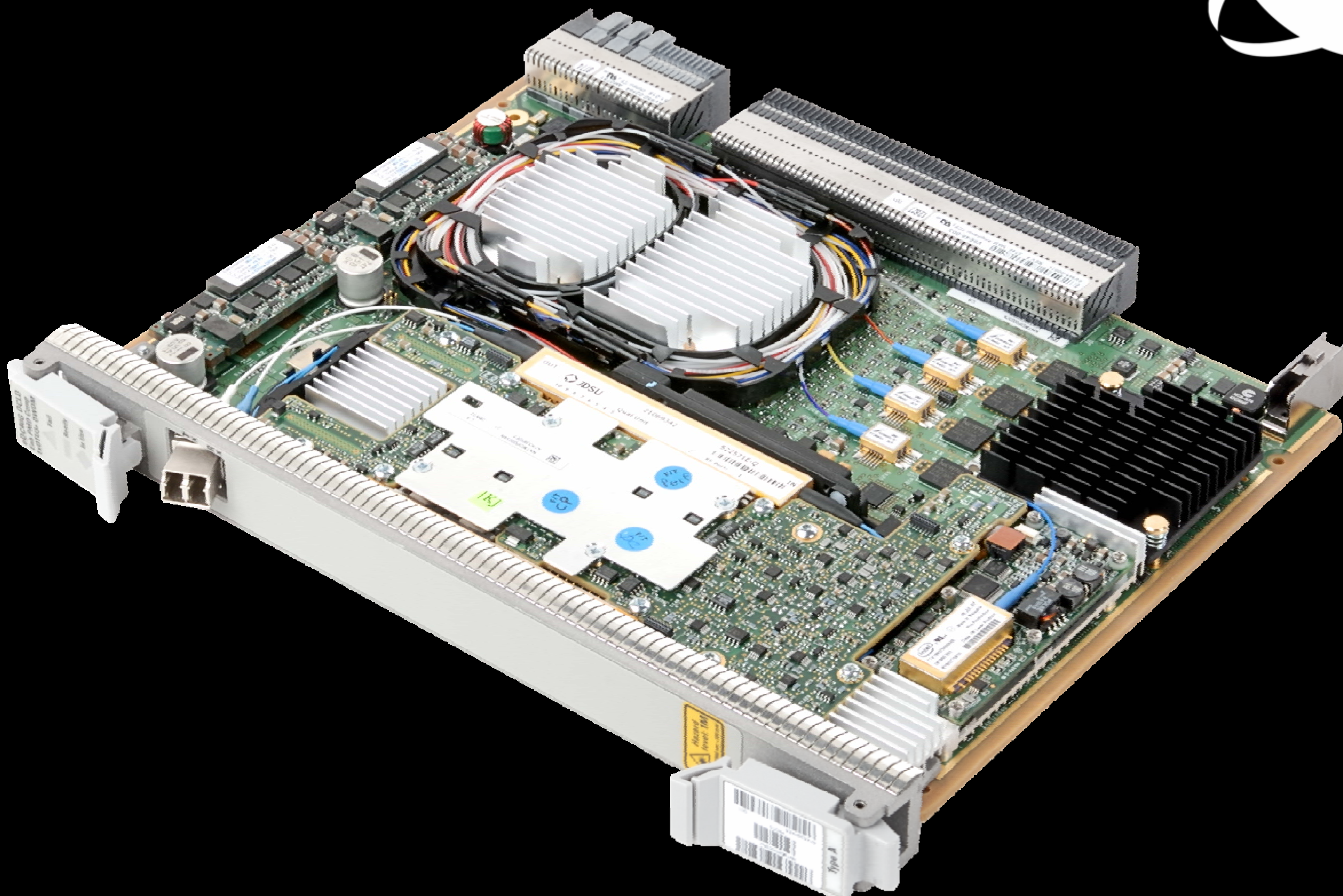
12 T Ops per second

Four 20 Gs/s 6 bit ADC

21 Watts

Linear and nonlinear post-compensation of 40 Gb/s ±80,000 ps/nm, 25 ps mean PMD, 2 dB mean PDL

40 Gb/s Coherent Modem

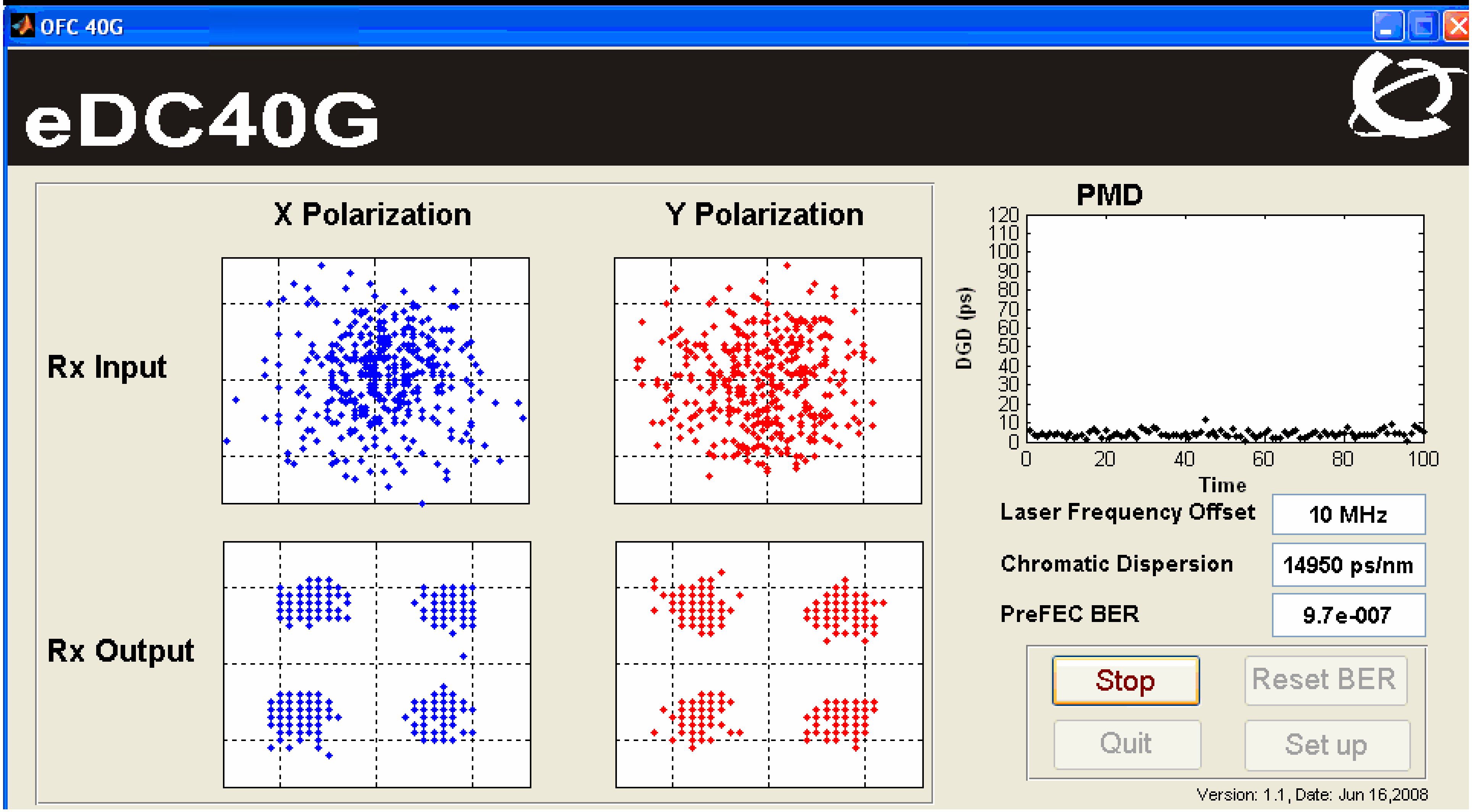


Real-time PMD tracking

> 1000 km of NDSF

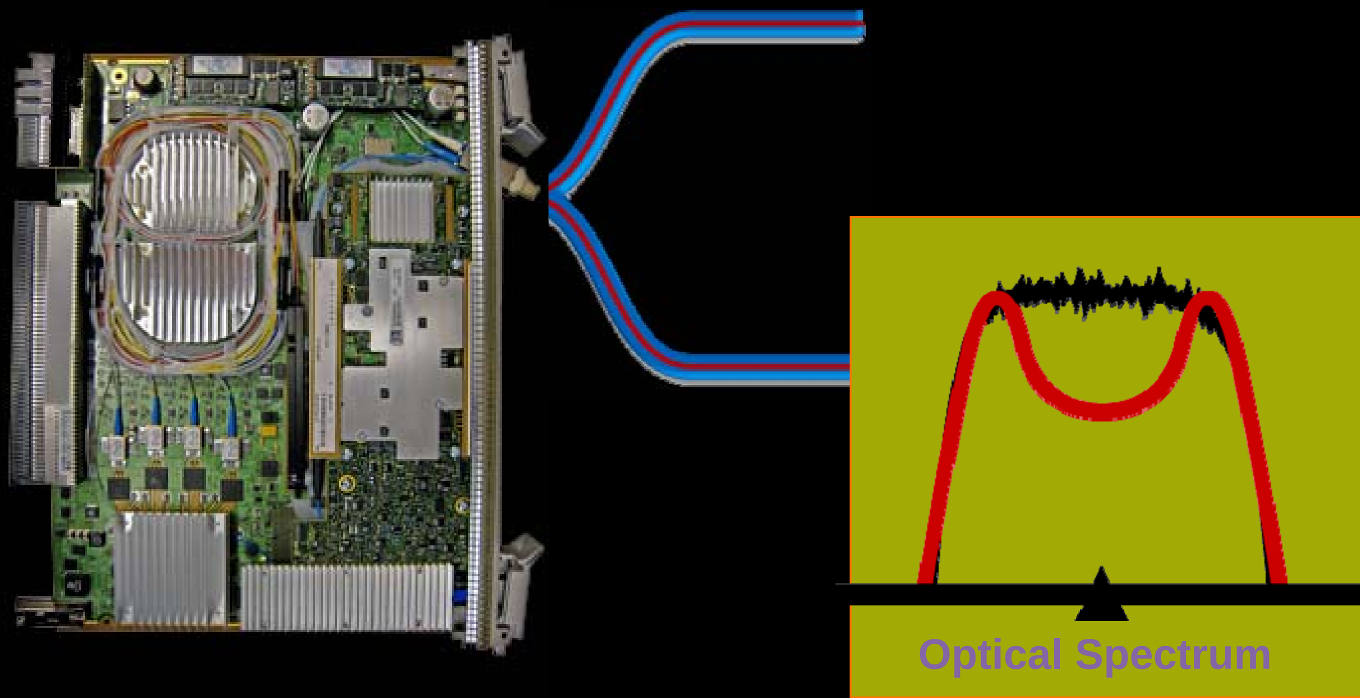
> 10G, 40G, and 100G at 50 GHz spacing

> JDS PMD emulator



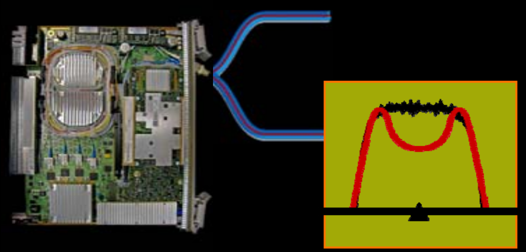
Coherent 100G

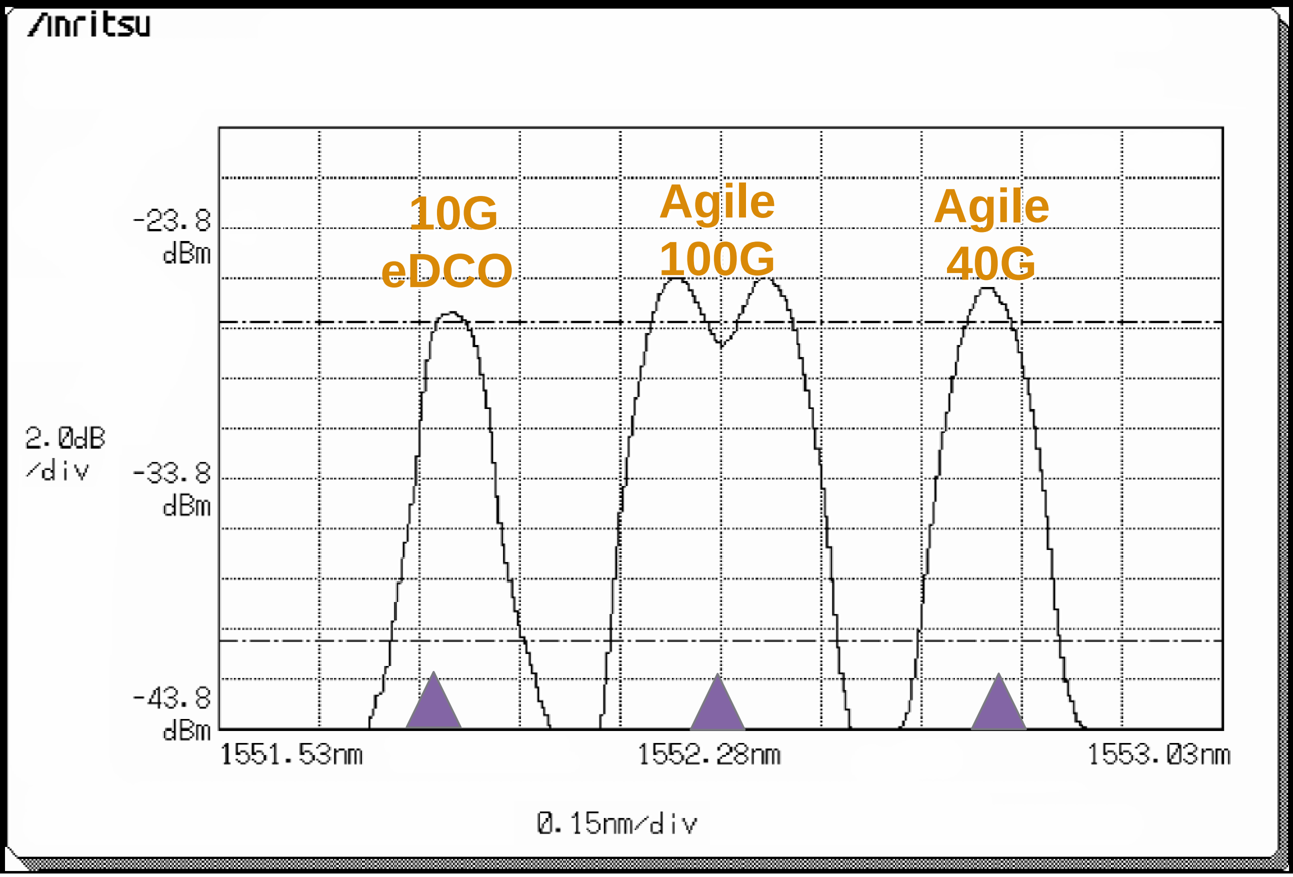
Agile 100G OFDM



- Two subcarriers 20 GHz apart
- 50 GHz channel spacing provides 9 Tb/s in C-band
- 1000 km reach, +/- 50,000 ps/nm, 20 ps mean DGD
- 12 Wavelength Selective Switch (WSS) ROADMs

100G OFDM

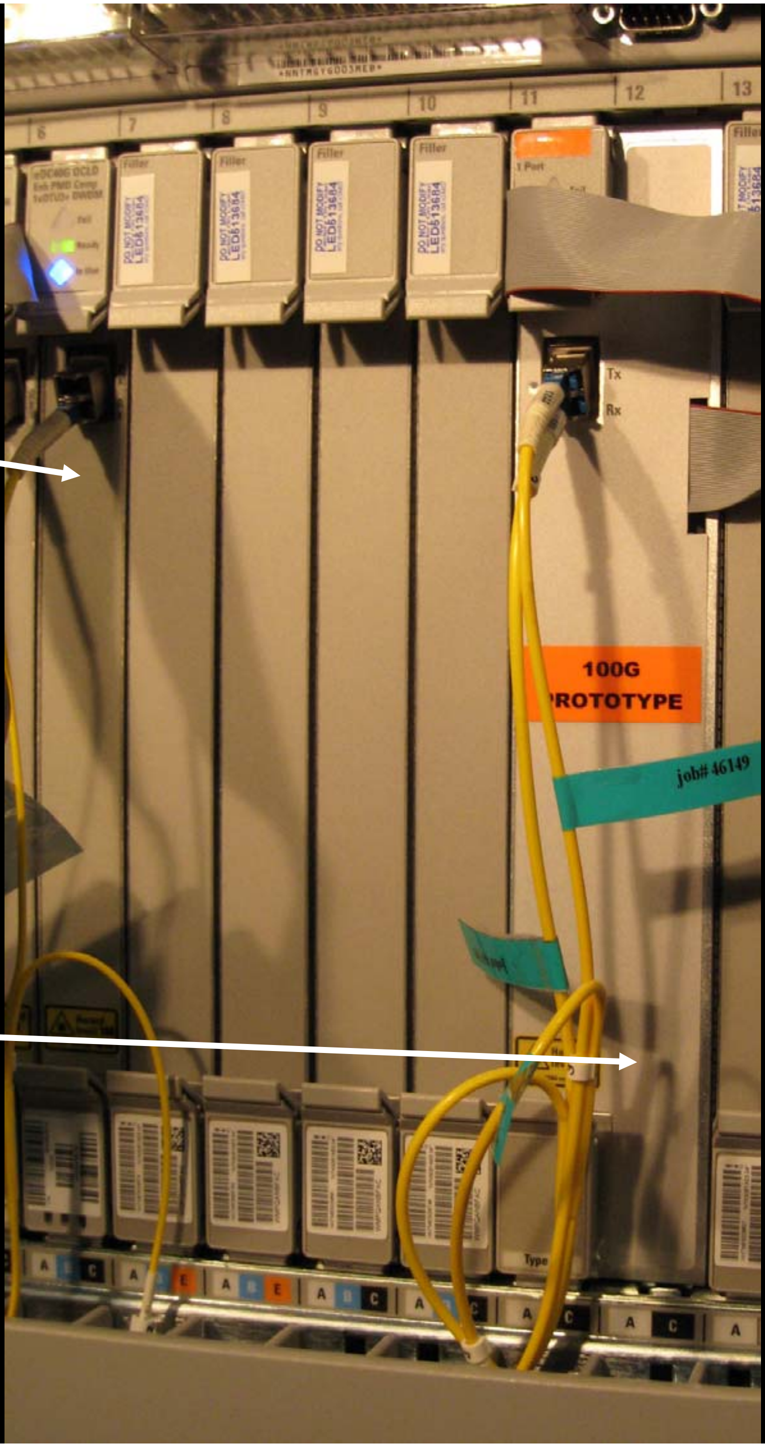




/inritsu
-23.8 dBm
2.0dB /div
-33.8 dBm
-43.8 dBm
10G eDCO
Agile 100G
Agile 40G
1551.53nm
1552.28nm
1553.03nm
0.15nm/div

40G Card

100 G Prototype



40,100 G Evolutions

>Evolutionary improvements in the usual way:

- Smaller
- Less Heat
- Lower Cost
- Greater Performance

Then What?

200G, 400G, 1000G

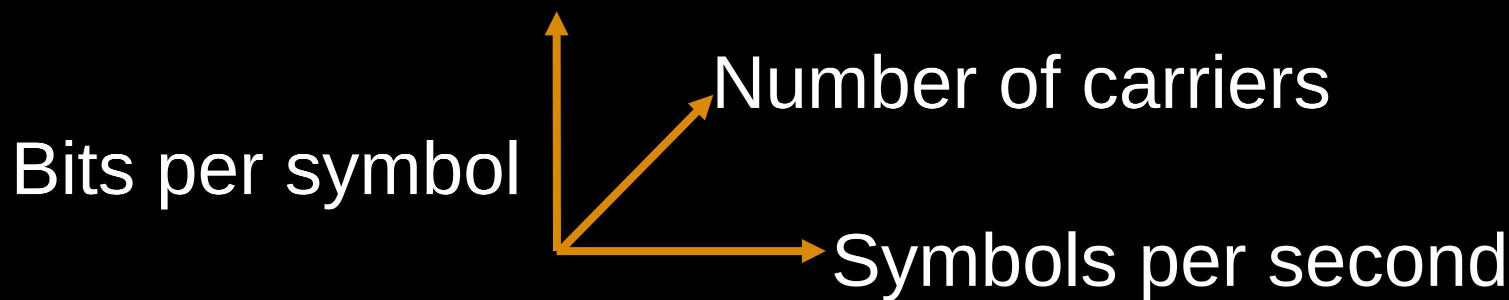
>Lower cost per bit

>More bits per fiber

>Larger packet streams

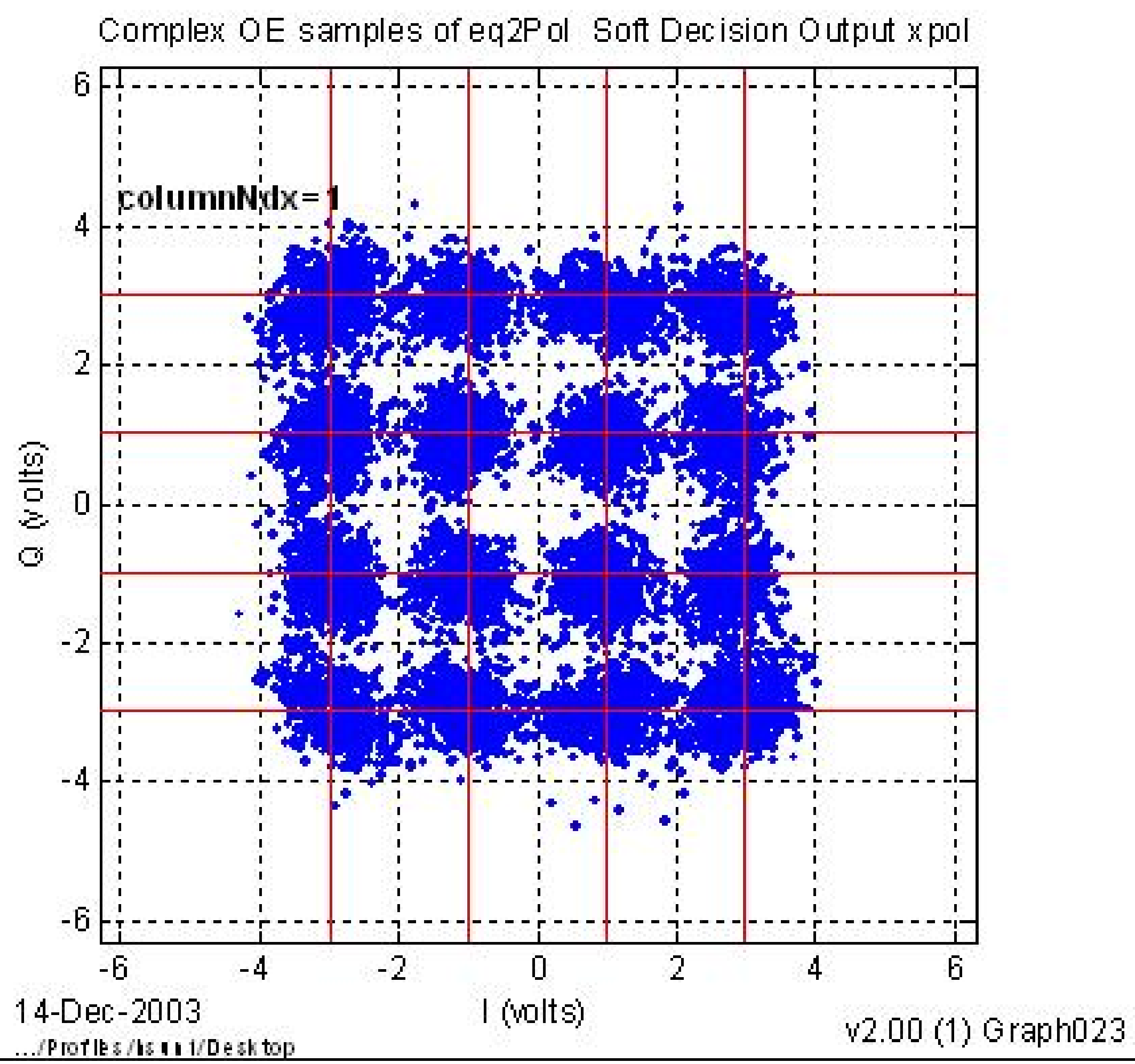
(From here on are my personal speculations and not product delivery commitments.)

Lightpath Bit Rate



The bit rate is the product of these three dimensions

More Bits per Symbol



More Symbols per Second

>Faster A/D

>More gates of DSP

>CMOS riding Moore’s Law

- Bipolar is too hot and does not have the gate count

Multiple Carriers

>Coherent Frequency Selection

>OFDM

>New ideas

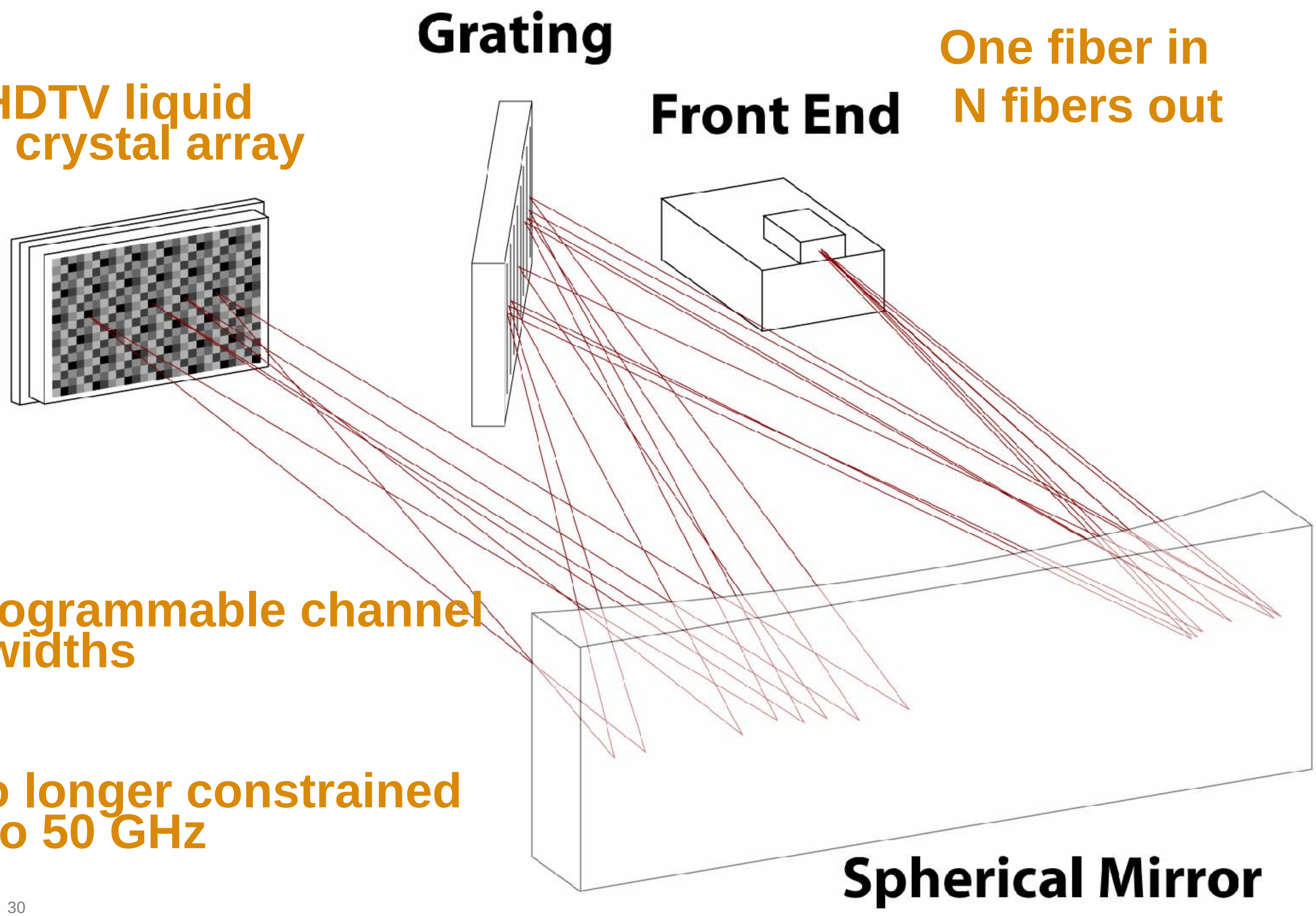
End of Fixed Channelization

>Static 50 GHz grid will not support 1000 Gb/s

- At 4 b/s/Hz need 250GHz of spectrum

>Need Flexible WDM

Flexible Spectrum Selection



HDTV liquid crystal array

One fiber in N fibers out

Programmable channel widths

No longer constrained to 50 GHz

Not generally economic by 2020

- Optical Regenerator
- Wavelength Converter
- OTDM
- Optical Demux
- Optical Burst Switch
- Optical Packet Switch
- Quantum Key Distribution
- Chaos Encryption
- Optical Logic
- Optical CDMA
- Soliton WDM
- …

2010-2020

- Cheap flexible optical spectrum
- Coherent modems
  - As 40G gets cheap and small it moves into the campus
  - 100G, 200G, 400G, 1000G, each become cost effective first in long haul, then regional,…
  - Complexity kept in CMOS
- Eventually, a new kind of optical device
  - I do not presently see any likely candidates

Optical Research Topics

- >Wavelength Switching
  - Lower cost
  - Flexibility
  - ms switch times, transient suppression, …
- >Modems
  - Lower cost
  - Higher performance
  - Higher capacity
- >New physics that may eventually have some application.

High Speed Challenge

> TCP, et al, assume random errors and congestion

> Layer 0/1/2 Lightpaths can easily be made error free
- Random bit error rate, packet loss rate < 10^{-20}

> Redundancy engineered as desired to react to failures
- 50 ms, seconds, minutes

> Latency and heat critical for many high speed applications
- Cannot afford ARQ buffers

> What is a protocol optimized for this environment?

> How can this be cleanly layered?

Traditional solution:
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 dispersion compensation engineered for a particular end-to-end connection,

Dispersion Tolerance

Dispersion is not precisely determined when designing a link, and dynamically changes.

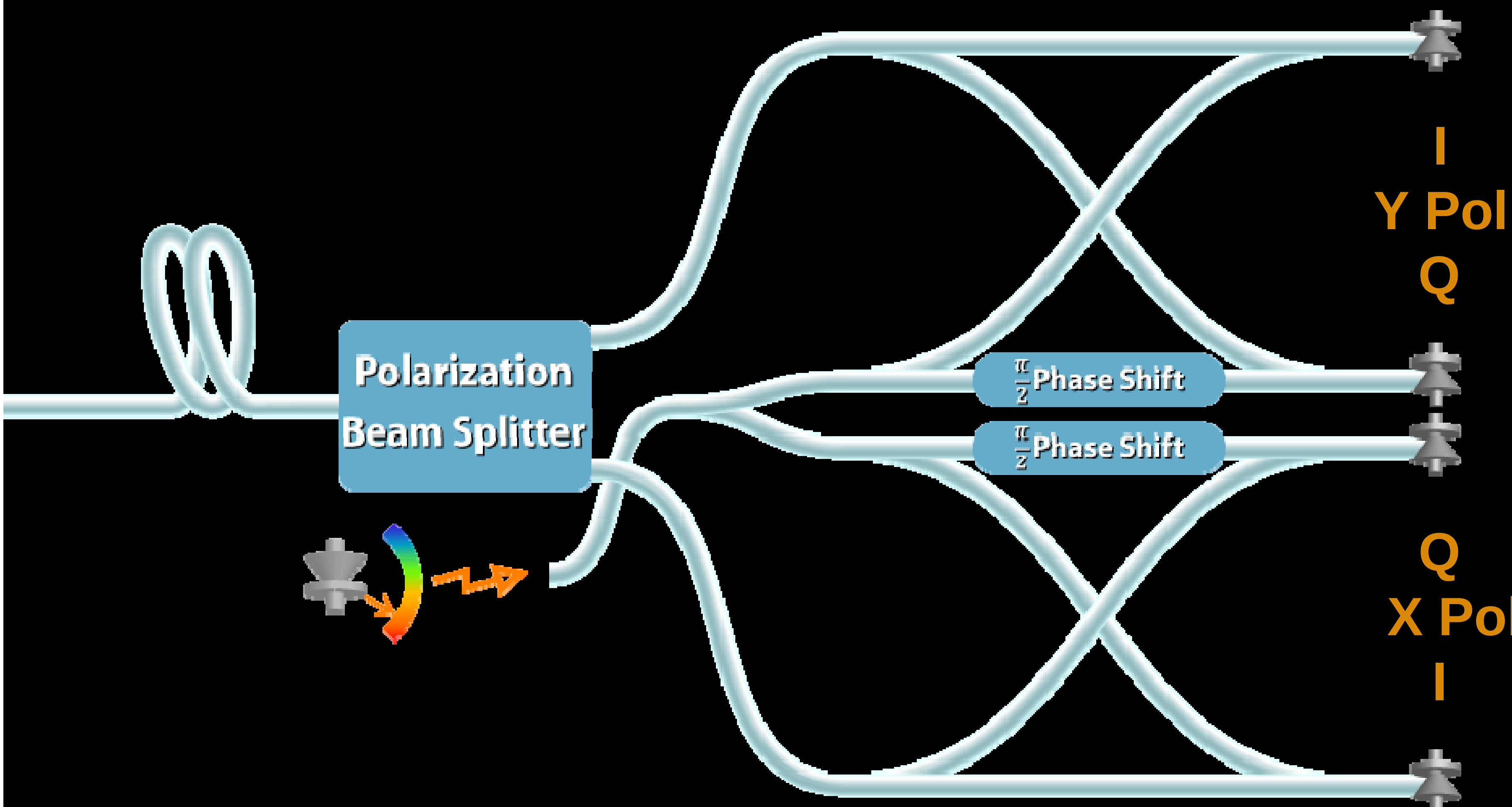
Each of these effects are budgeted lower and upper bounds, depending upon fiber type, cable type, geography, and equipment type.

- Fiber temperature variation
- DCM temperature drift
- EDFA dispersion
- Fiber measurement error
- Second order PMD effects
- WDM demux dispersion variation
- Wavelength Selective Switch dispersion variation
- Dispersion specification mismatch error
- Repair reroutes

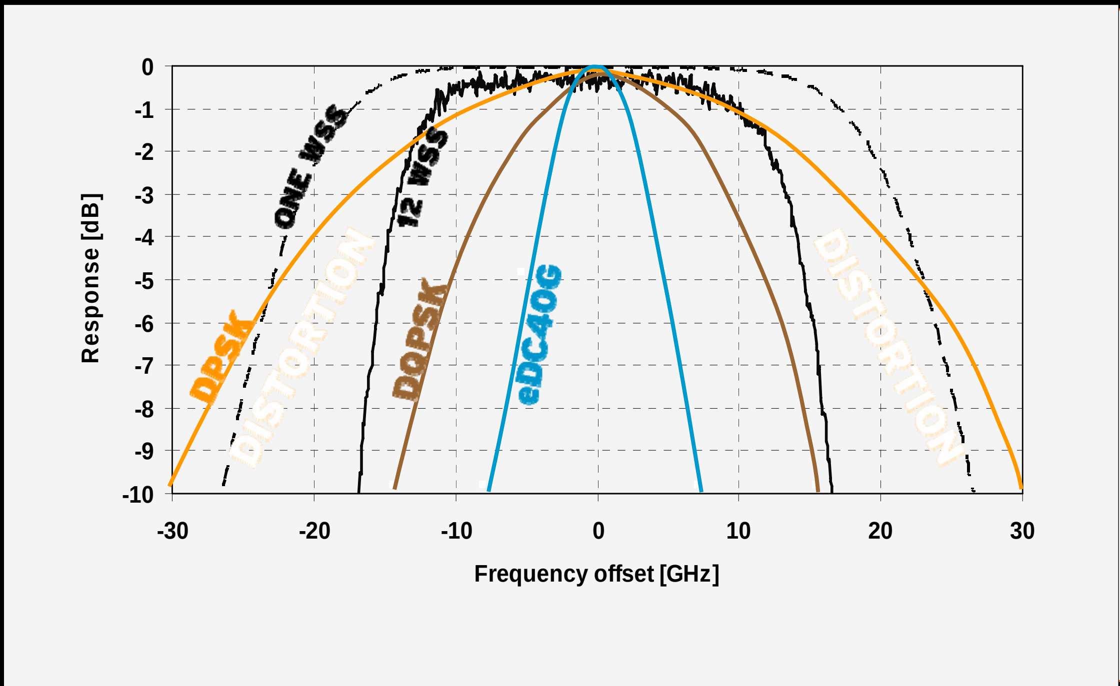
A typical dispersion spread is $\pm$400 ps/nm.

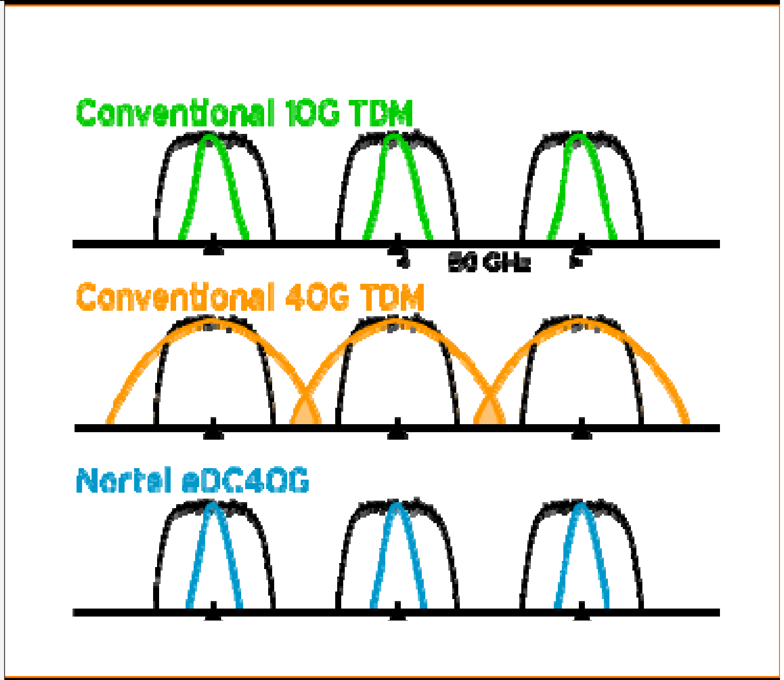
The system must be guaranteed to work everywhere in this range.

Coherent Detection



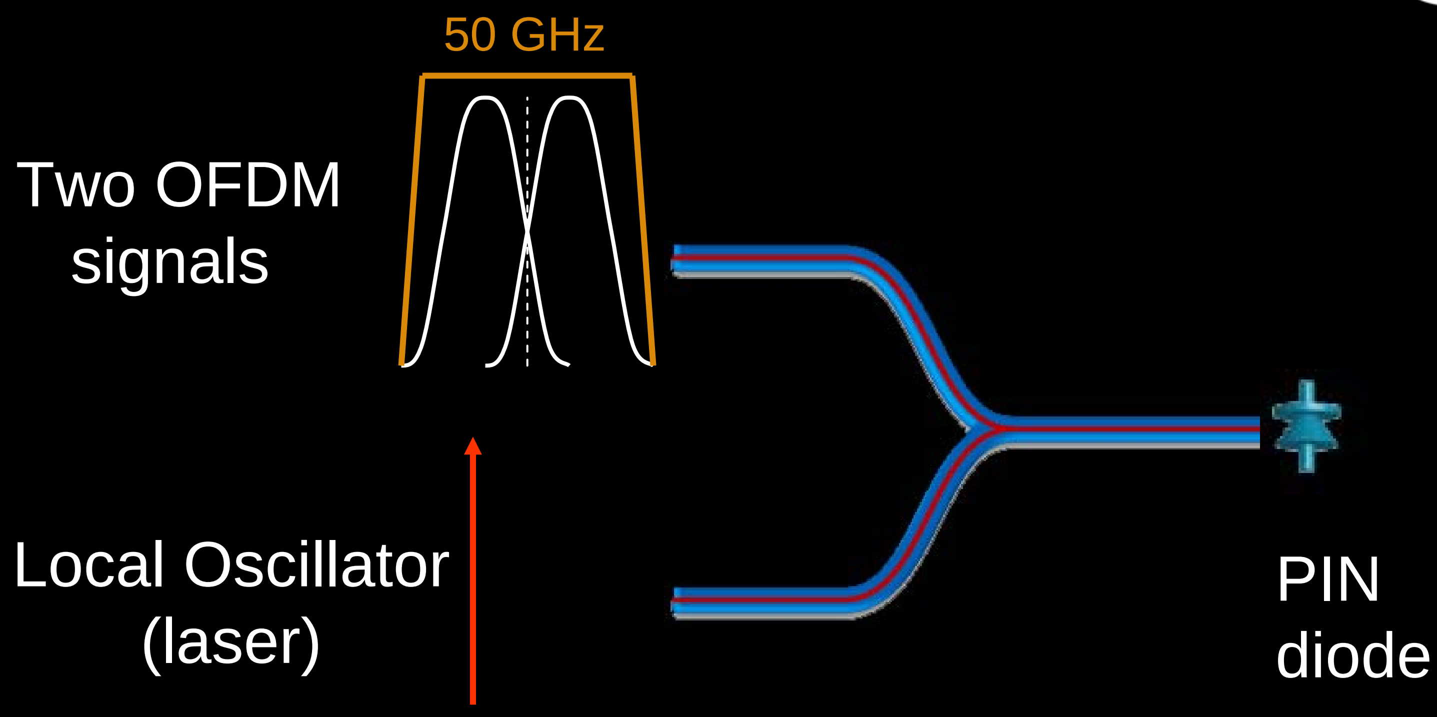
Filter Concatenation
50GHz Wavelength Selective Switch (WSS)





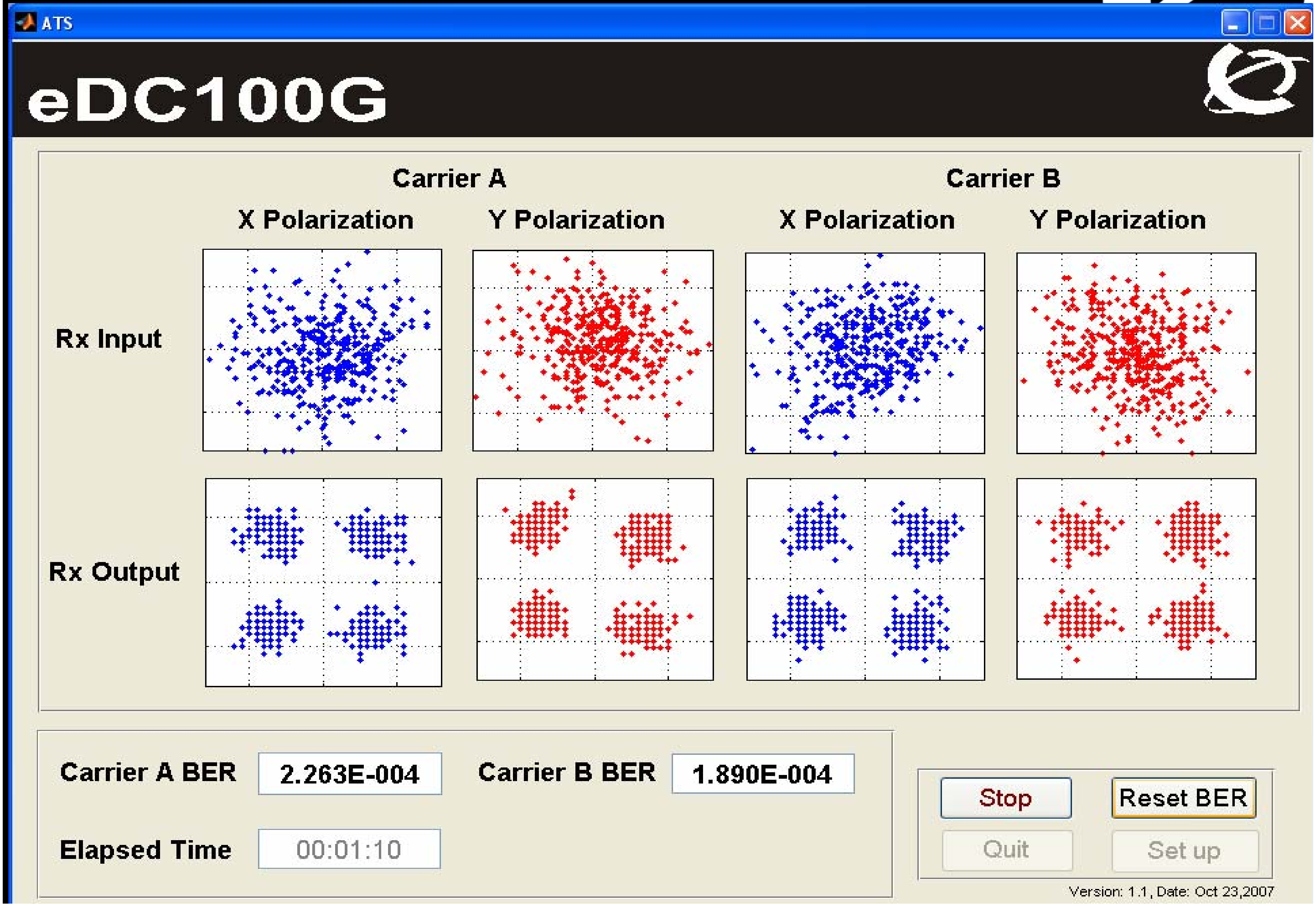
Conventional 40G TDM impacted severely by 50GHz filter concatenation

100G Optical FDM

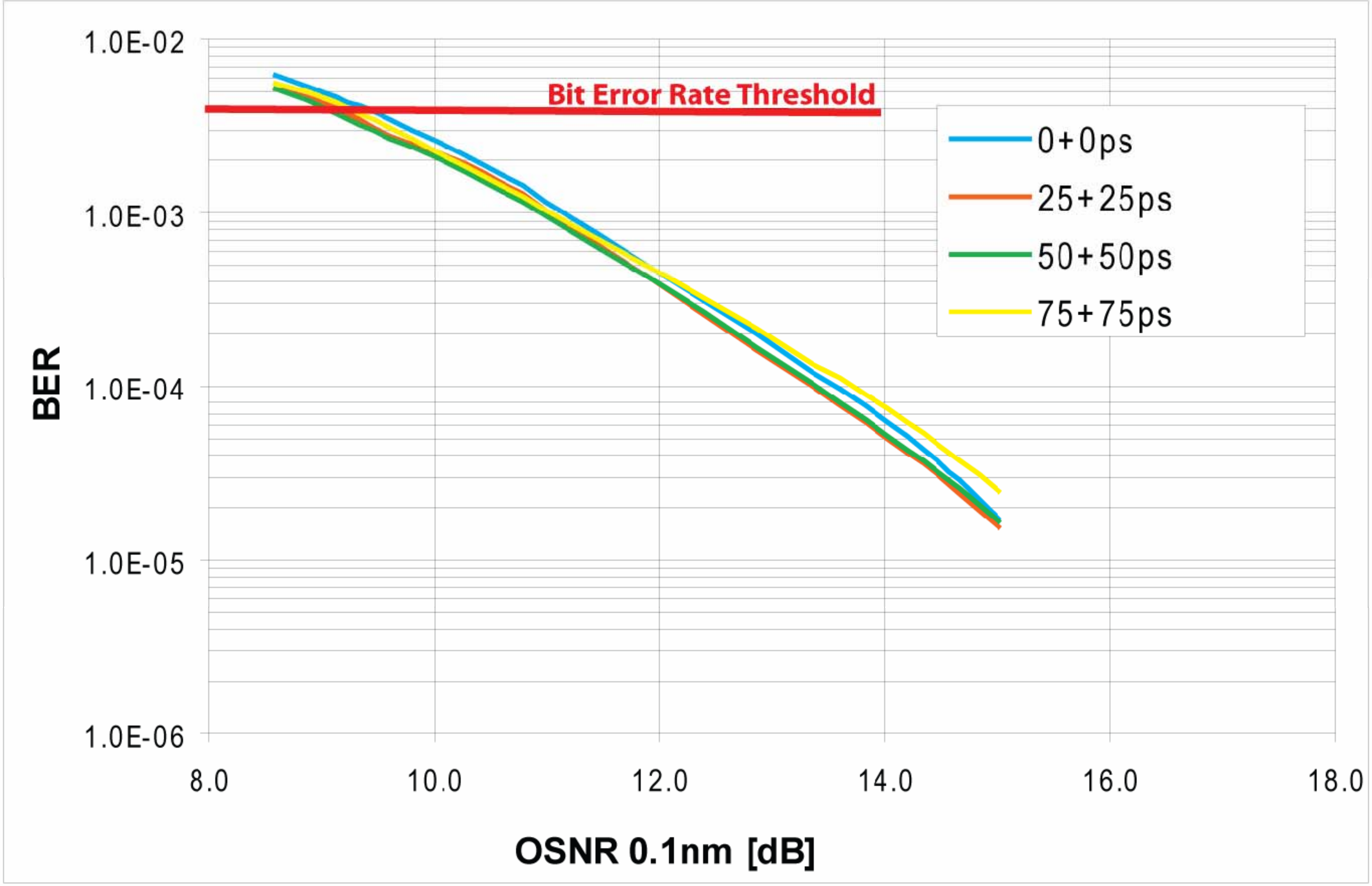


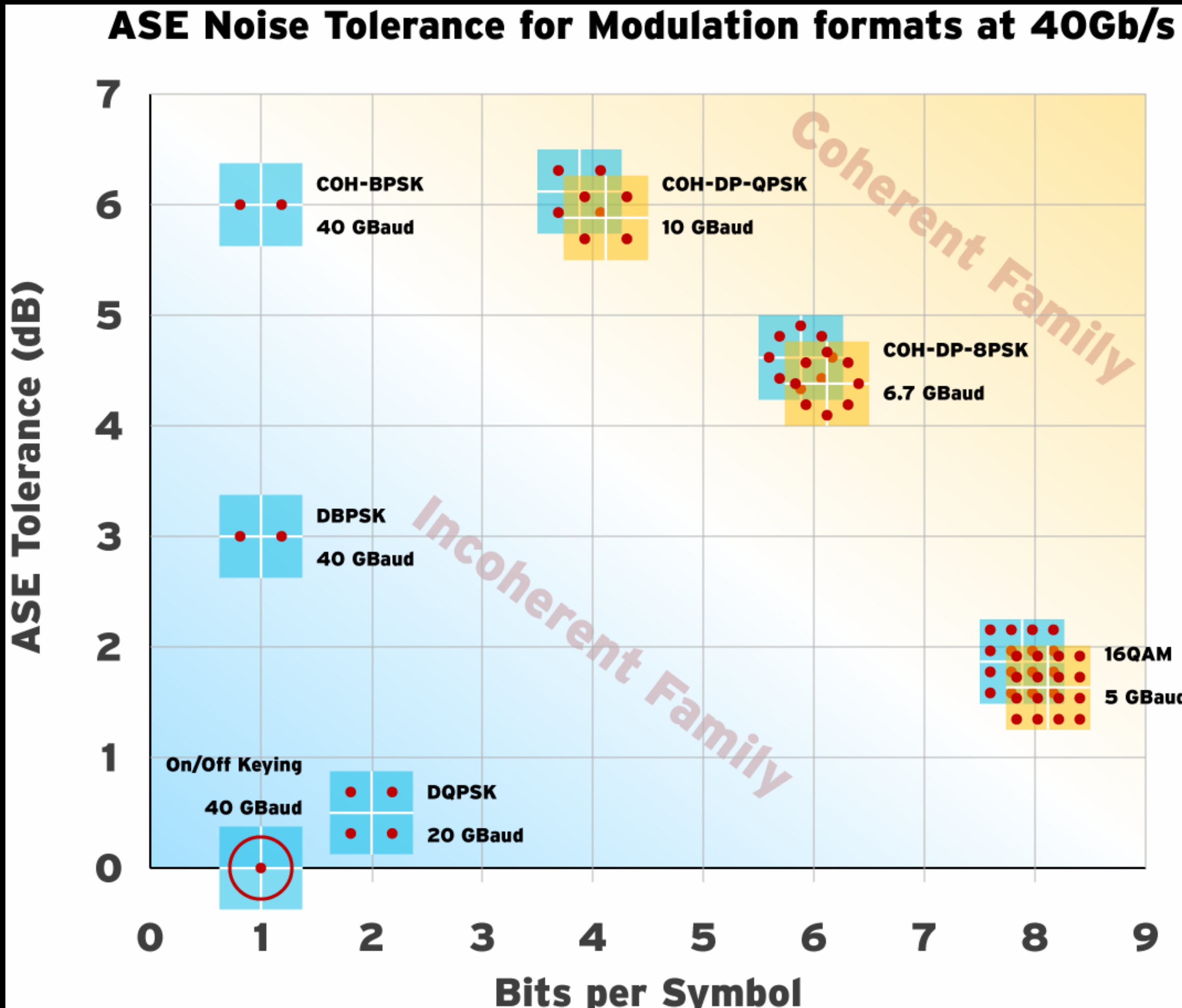
Coherent frequency selection within 50GHz channel

100G OFDM Real Time Data

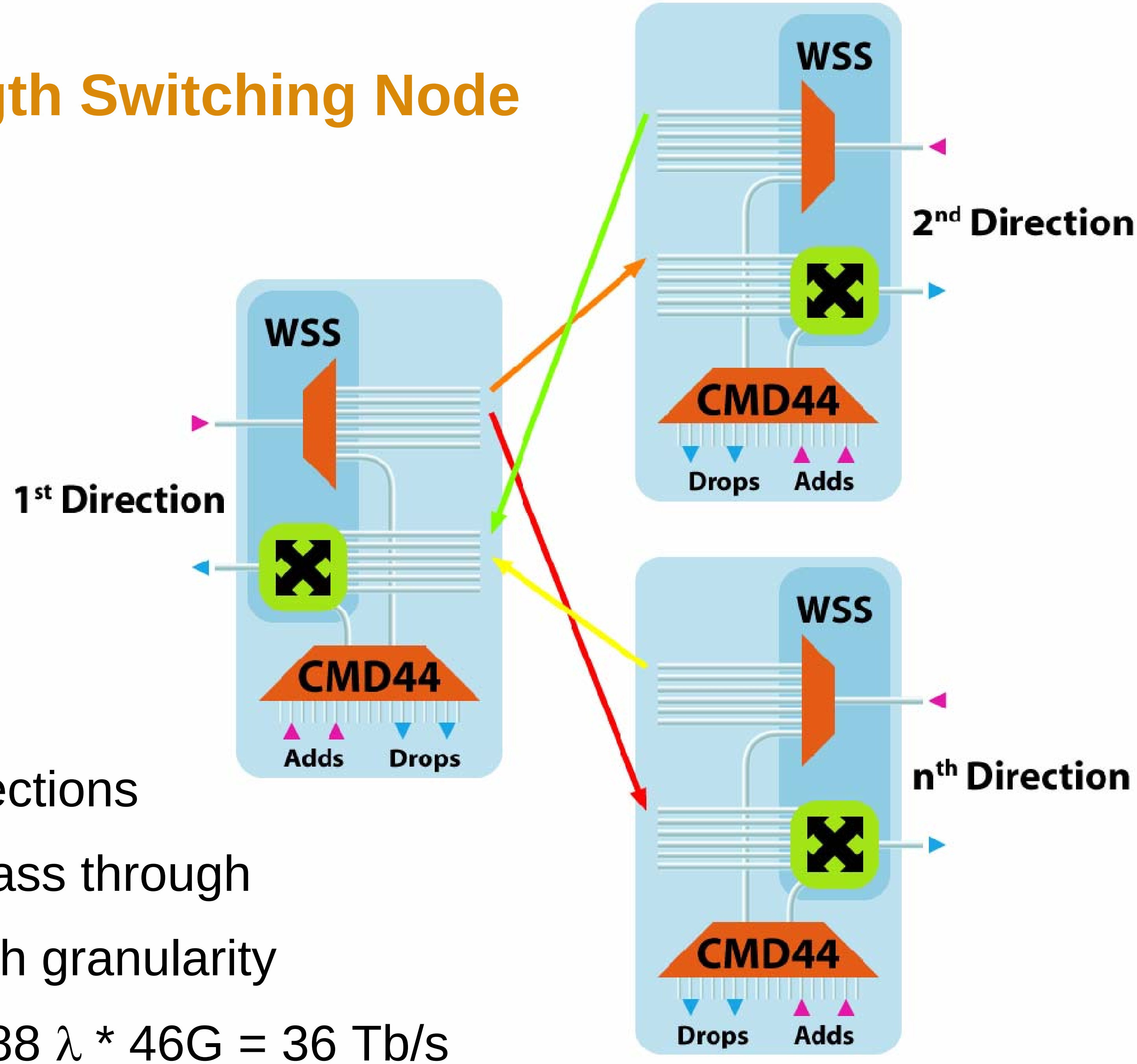


PMD Tracking




ASE Noise Tolerance for Modulation formats at 40Gb/s
ASE Tolerance (dB)
Bits per Symbol
0
1
2
3
4
5
6
7
8
9
COH-BPSK
40 GBaud
COH-DP-QPSK
10 GBaud
COH-DP-8PSK
6.7 GBaud
DBPSK
40 GBaud
16QAM
5 GBaud
On/Off Keying
40 GBaud
DQPSK
20 GBaud
Coherent Family
Incoherent Family

Wavelength Switching Node



> Up to nine directions

> Add-drop or pass through

> Per wavelength granularity

> 9 directions * 88 λ * 46G = 36 Tb/s