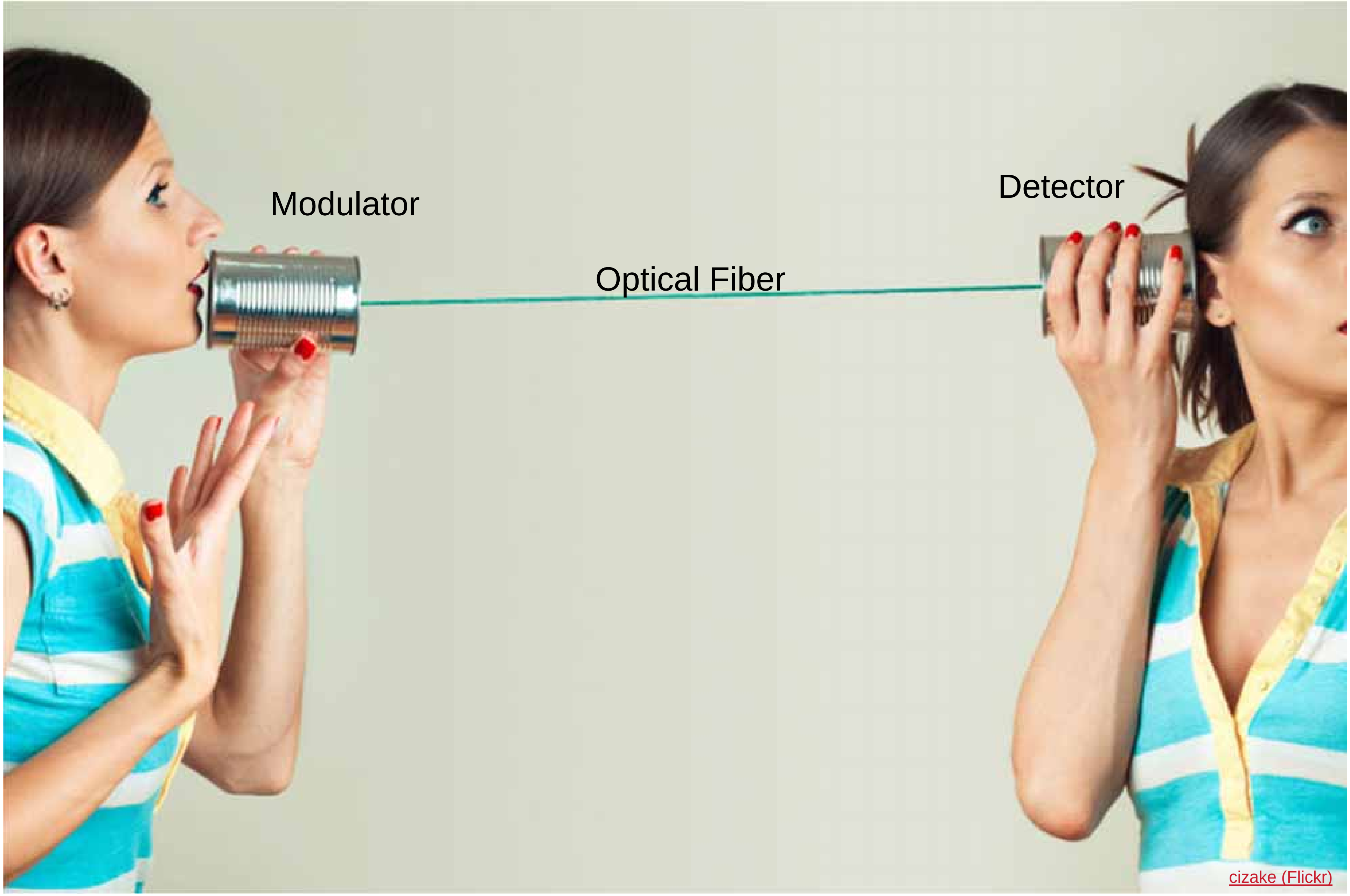
100G and Beyond
Coherent Optical Communications

Kim Roberts

Optical Fiber Communications



Reach Matters

in

Optical Transmission

(and ladders)

  4042238-stige.jpgwww.bt.dk

Spectral Efficiency Matters

- **Continued exponential growth of 30%-50%**
  - >1000 Tb/s of new end-to-end traffic in year 2020
  - Optical Spectrum Squeezed for Bits/Second/Hz

Latency Matters

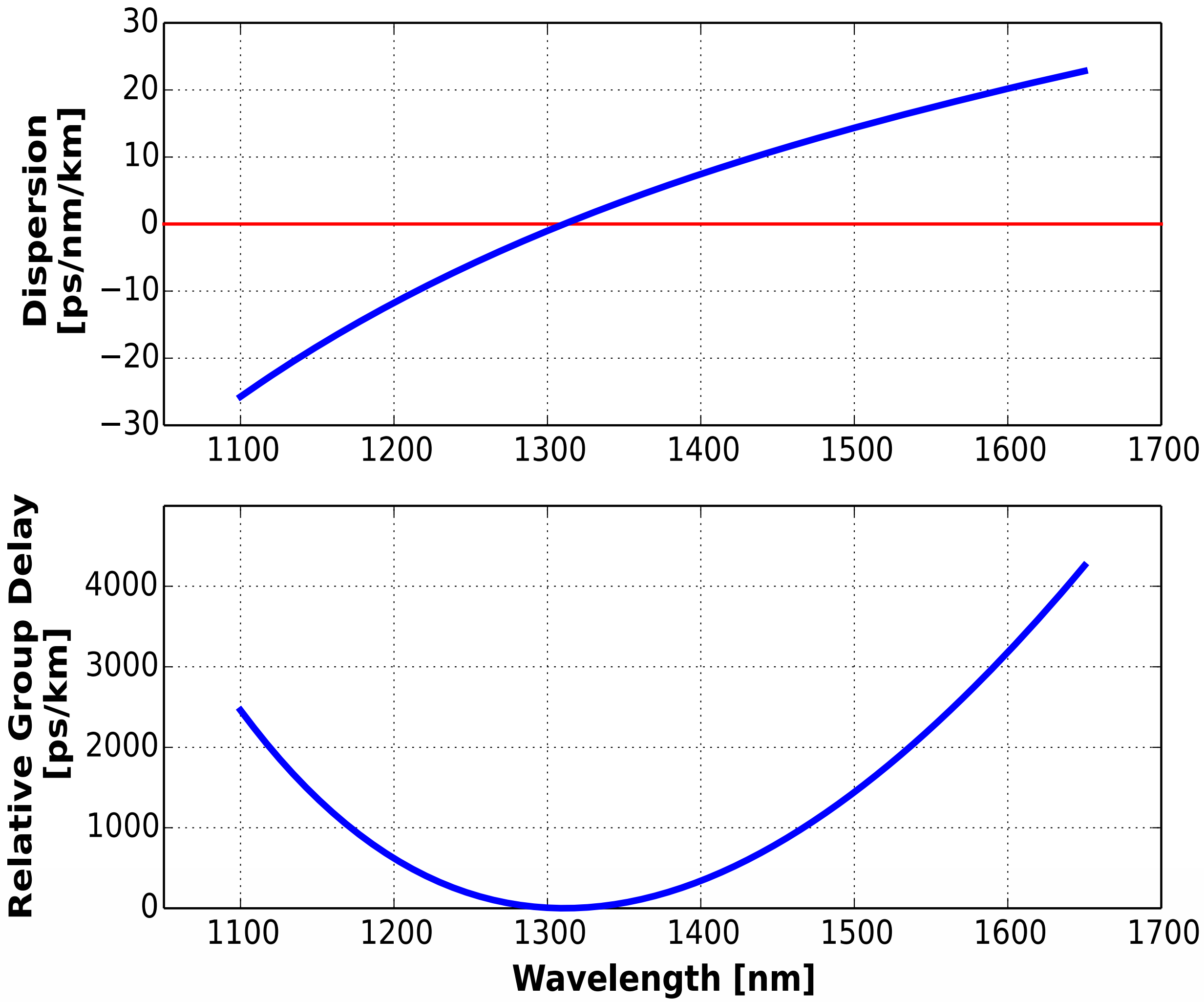
Cost Matters

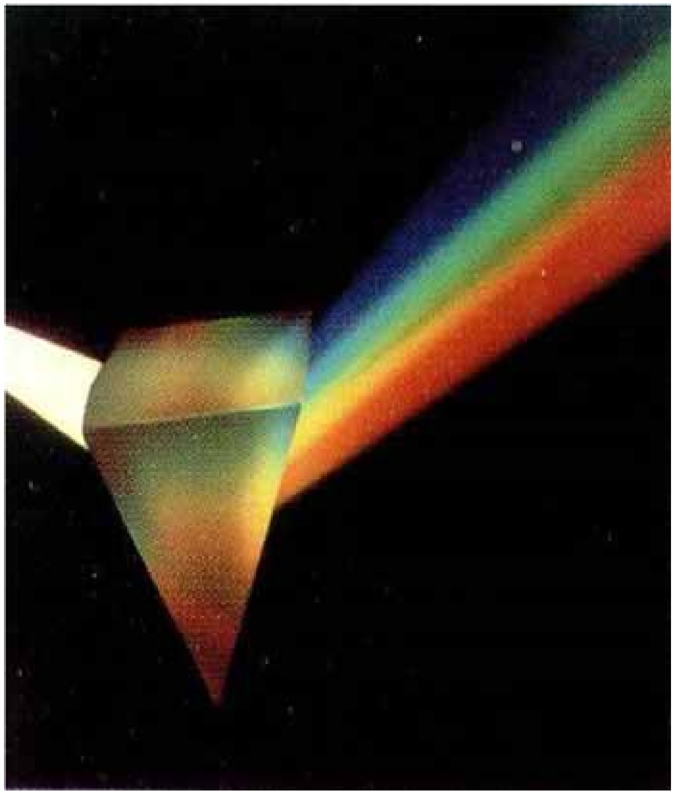

Heat Matters
www.bansheemann7.com

Physical Barriers

http://www.nrel.colostate.edu/project

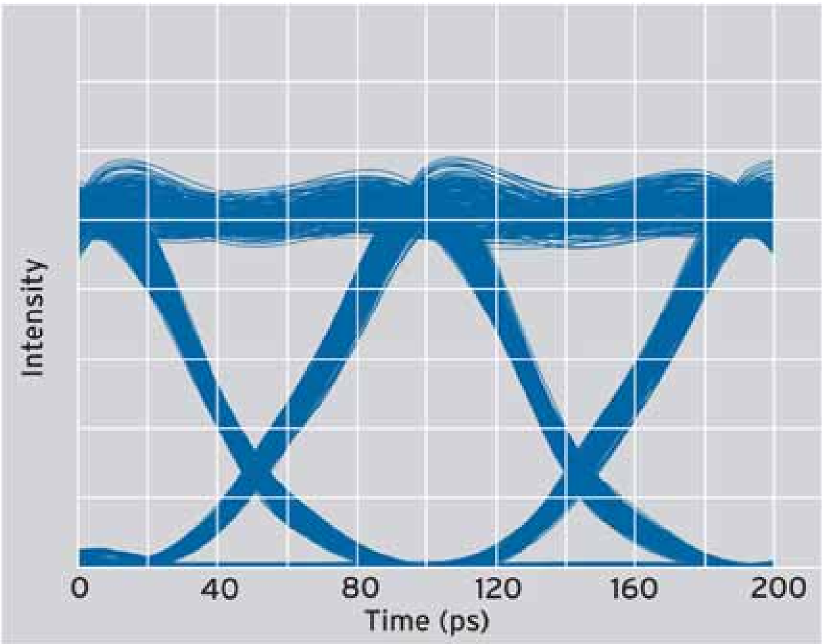
Chromatic Dispersion



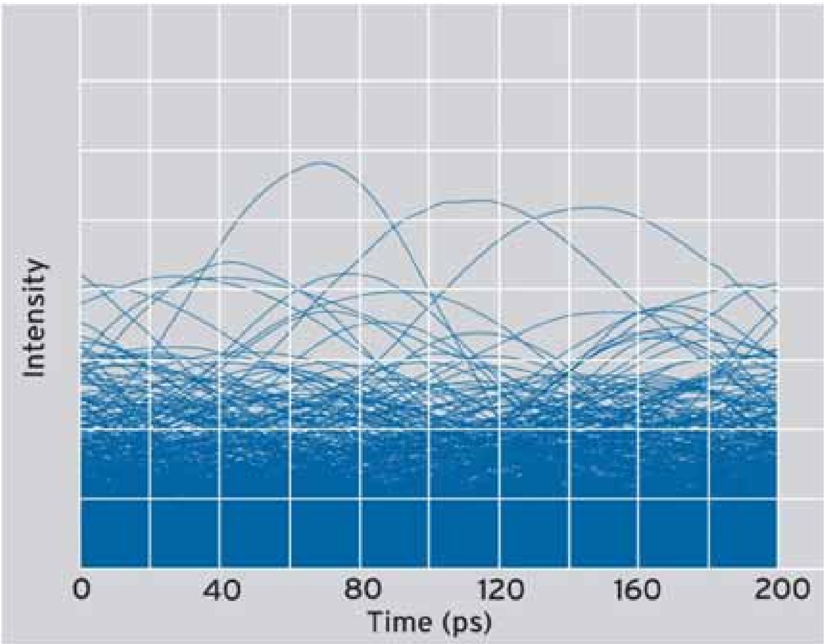


physics.utoledo.edu

Chromatic Dispersion

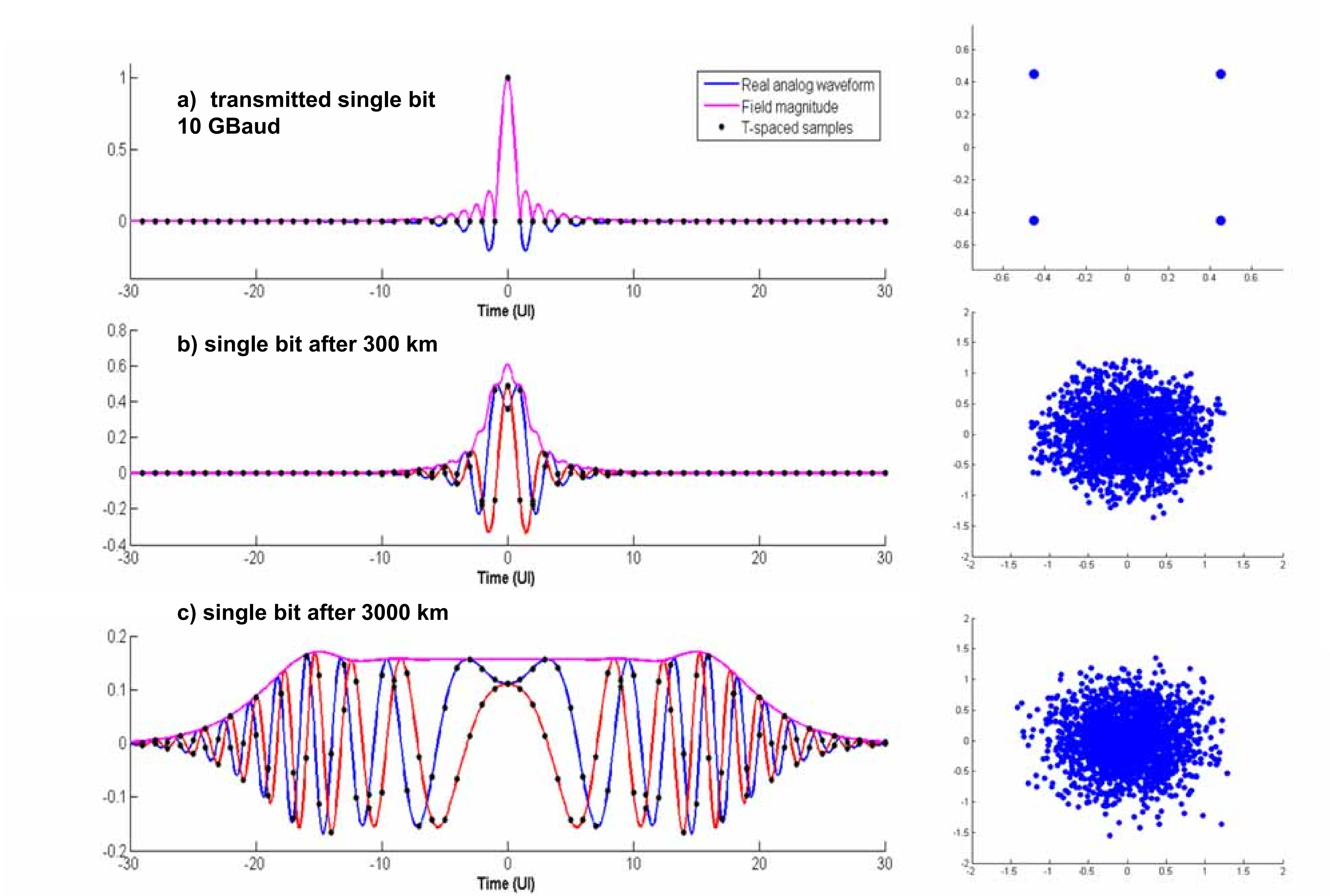


Transmitted 10G Signal



Signal after Dispersion

Linear fiber propagation

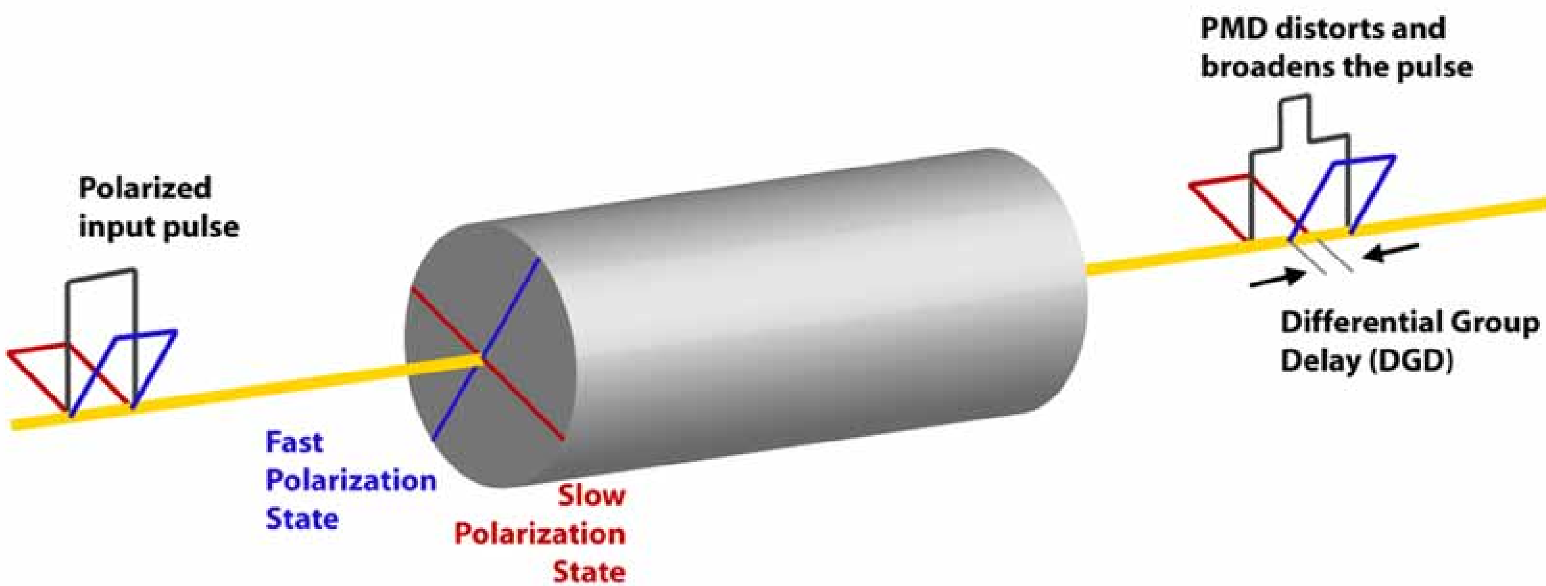


Traditional solution: Dispersion Compensation Modules

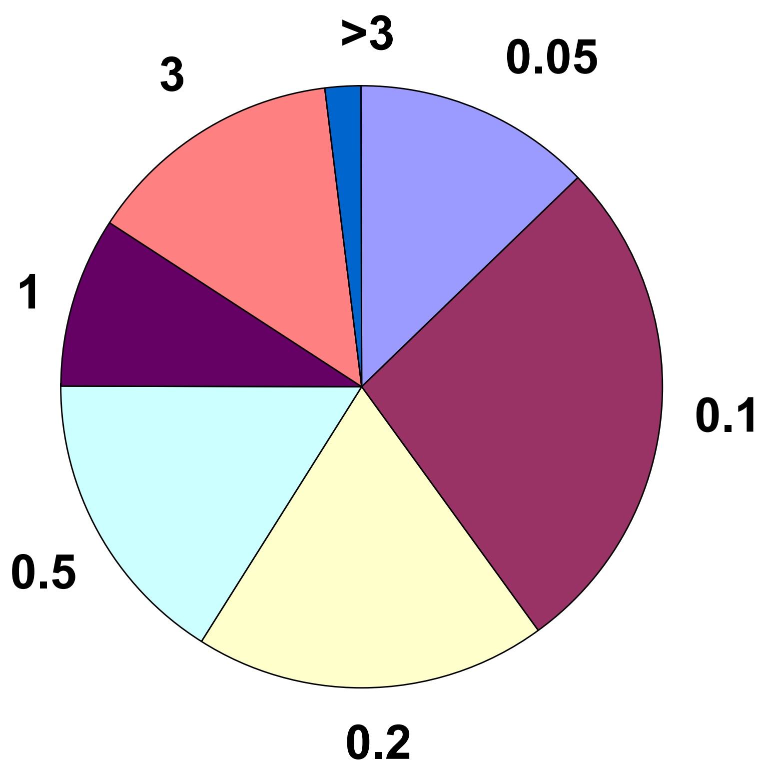
- Coils of 1 to 20 km of special fiber
- 5 μs to 100 μs of added delay per coil
- $3k to $10k per module

- Each line amp site needs a specific value of dispersion compensation engineered for a particular end-to-end connection,

Polarization Mode Dispersion (PMD)



Mean PMD



- 2266 spans of 80 km measured
- Not including concatenation
- Average PMD of 0.75 ps/√km
- Worst = 27.4 ps/√km

Mean PMD in ps/√km

Data from OFC 2007 workshop

richard.ednay@ott.co.uk & modesto.morais@iep.pt

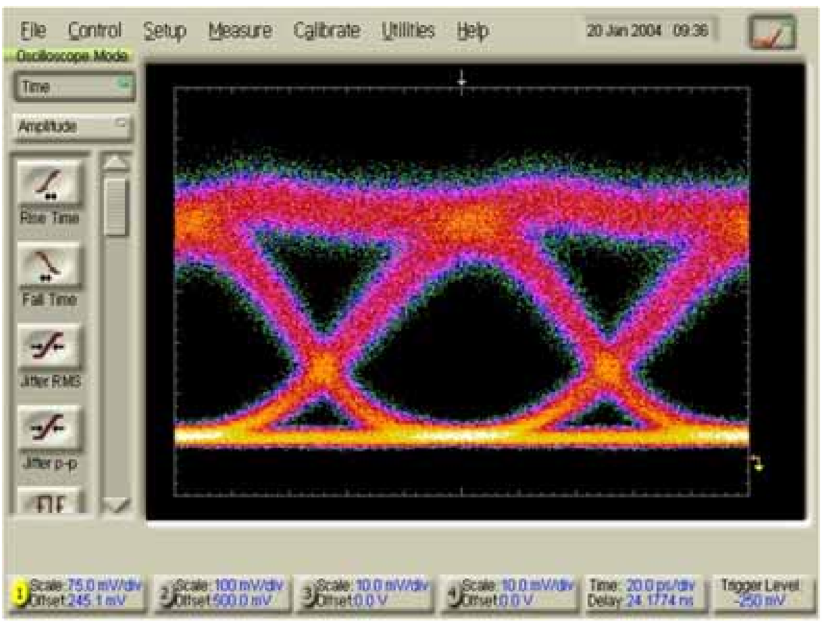
Noise

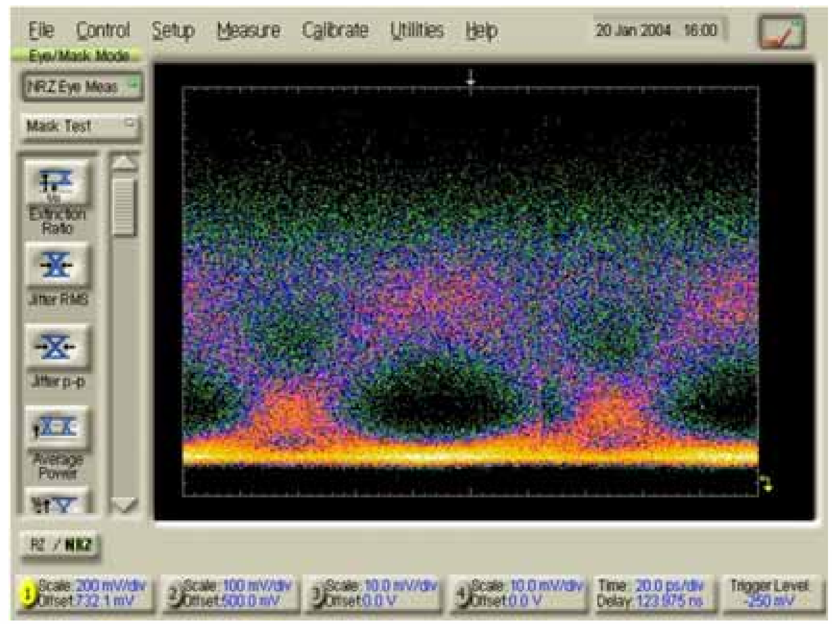
OSNR

- Optical Signal to Noise Ratio
- Power in optical signal divided by the power in 0.1 nm of the noise spectrum
- Expressed in dB.
- For amplifiers and a line system, delivering a high OSNR is good.
- For a receiver, tolerating a low OSNR is good.

Amplified Spontaneous Emission (ASE)

- Amplifiers are used to overcome fiber losses.
- Optical Noise is added by each amplifier.





$$\rho(\lambda) = 2\, h\, \nu\, n_{sp}\, (G(\lambda) - 1)$$

Optical Fiber Nonlinearity

- **The Kerr effect** $n_{NL}(\omega) \approx n(\omega) + n_2 |E|^2$
- **Self Phase Modulation**
- **Cross Phase Modulation**

Fiber Attenuation

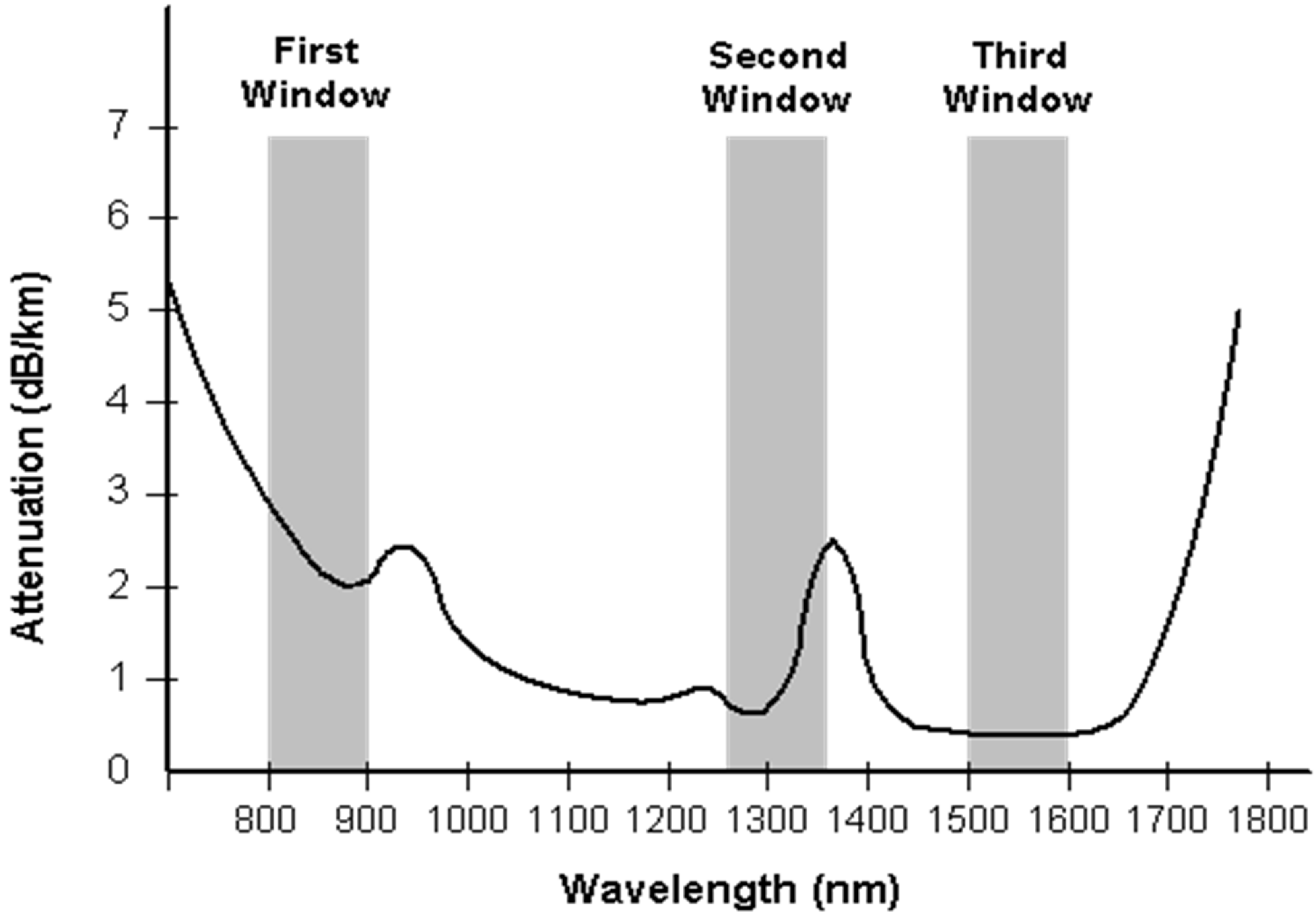
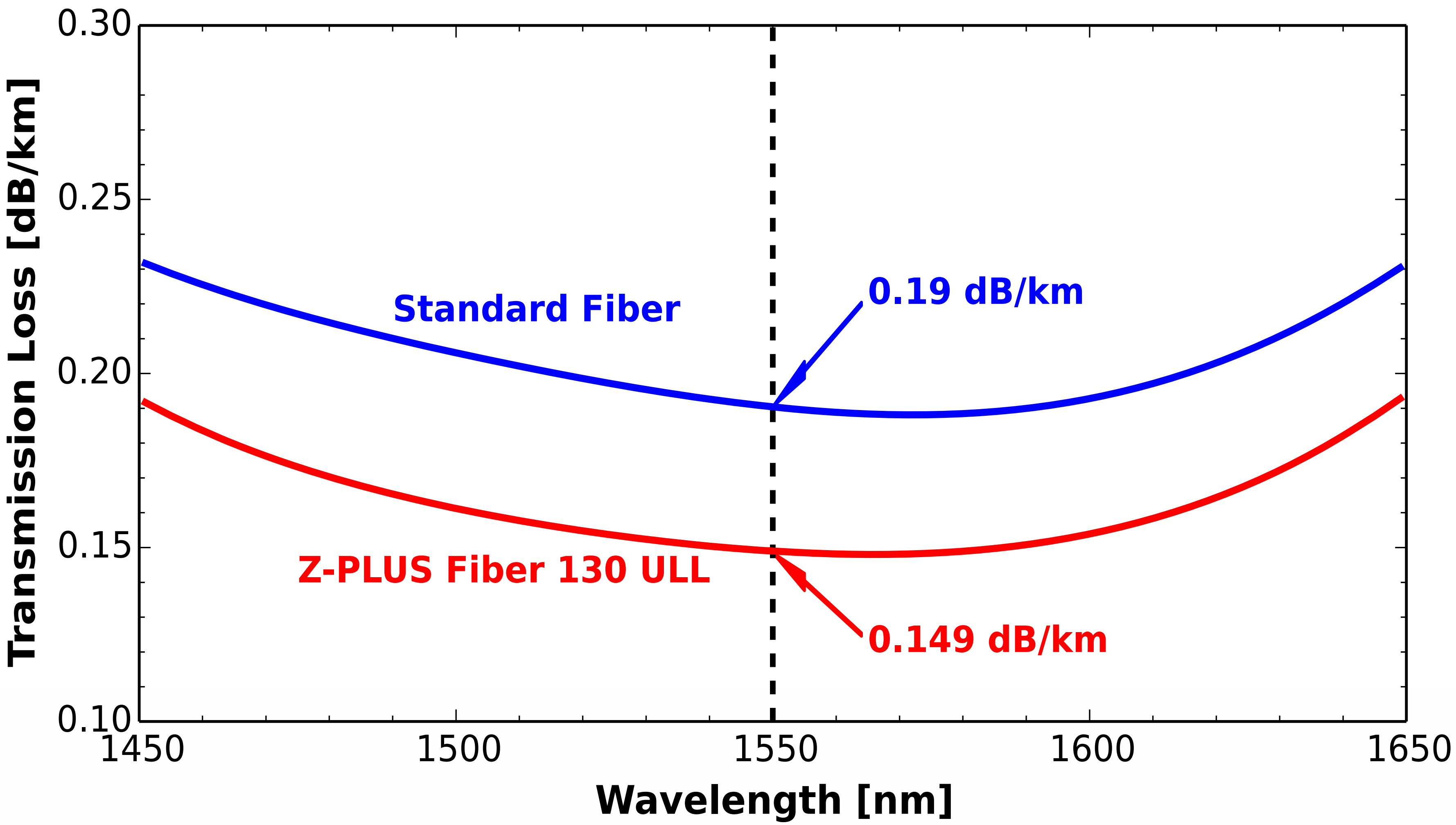
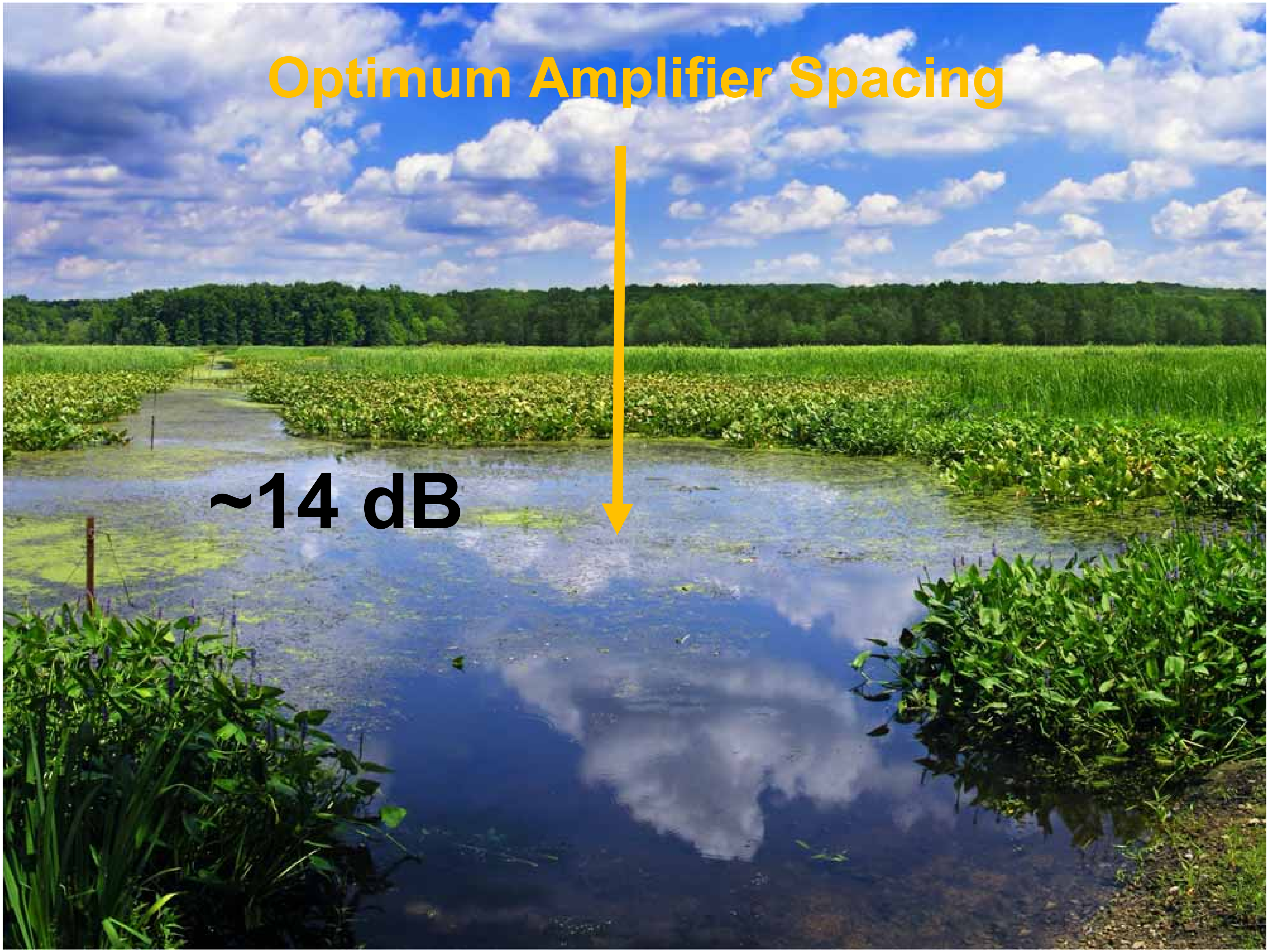


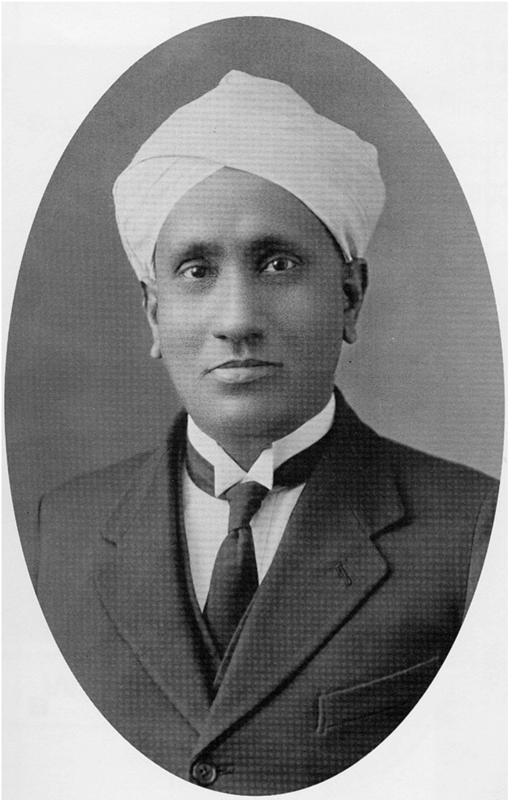
Figure from http://macao.communications.museum/images/exhibits

Low Loss Fiber

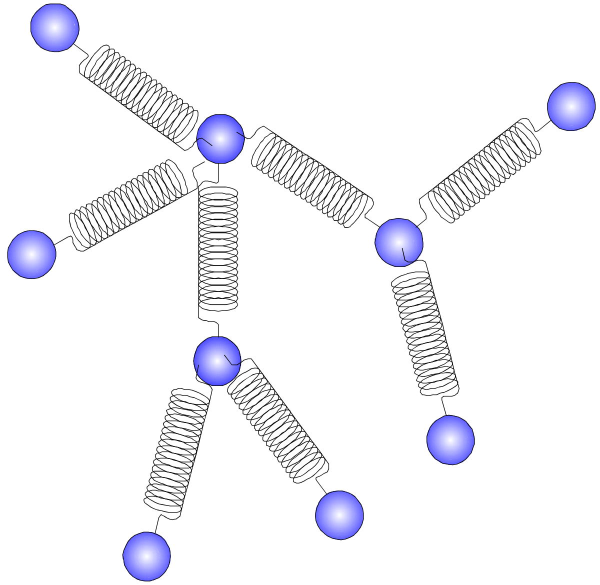


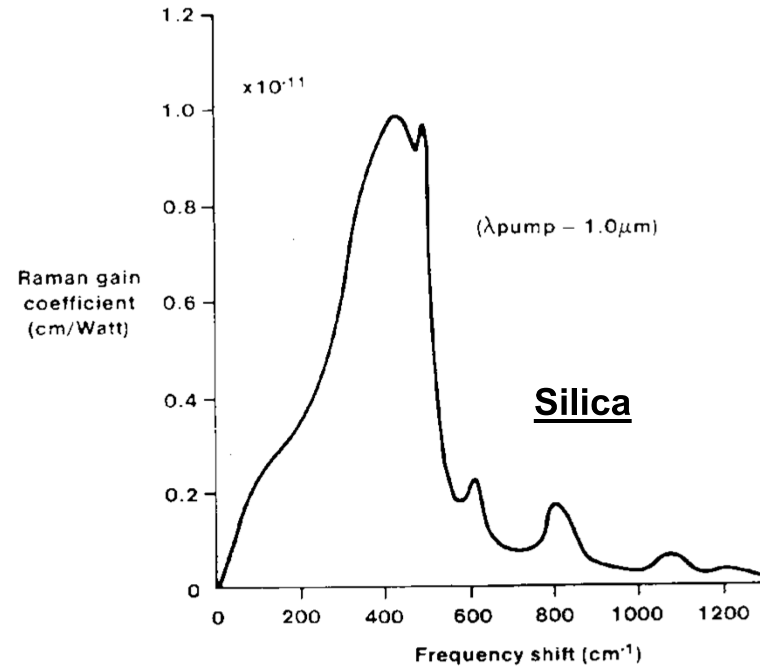

Optimum Amplifier Spacing
~14 dB

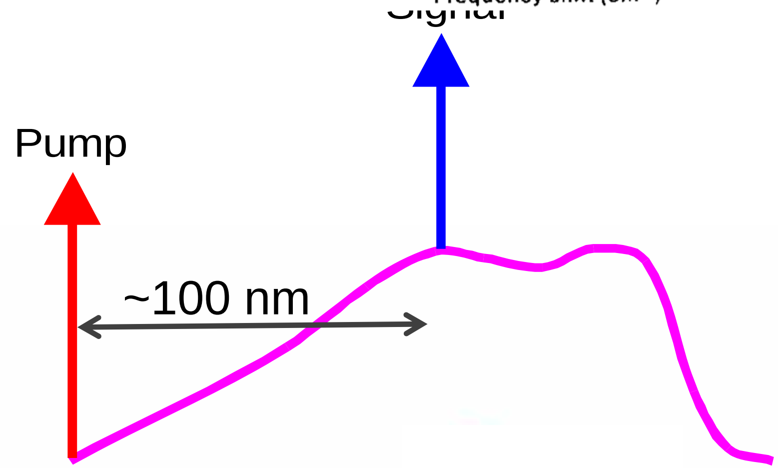
Raman Amplification



C.V. Raman

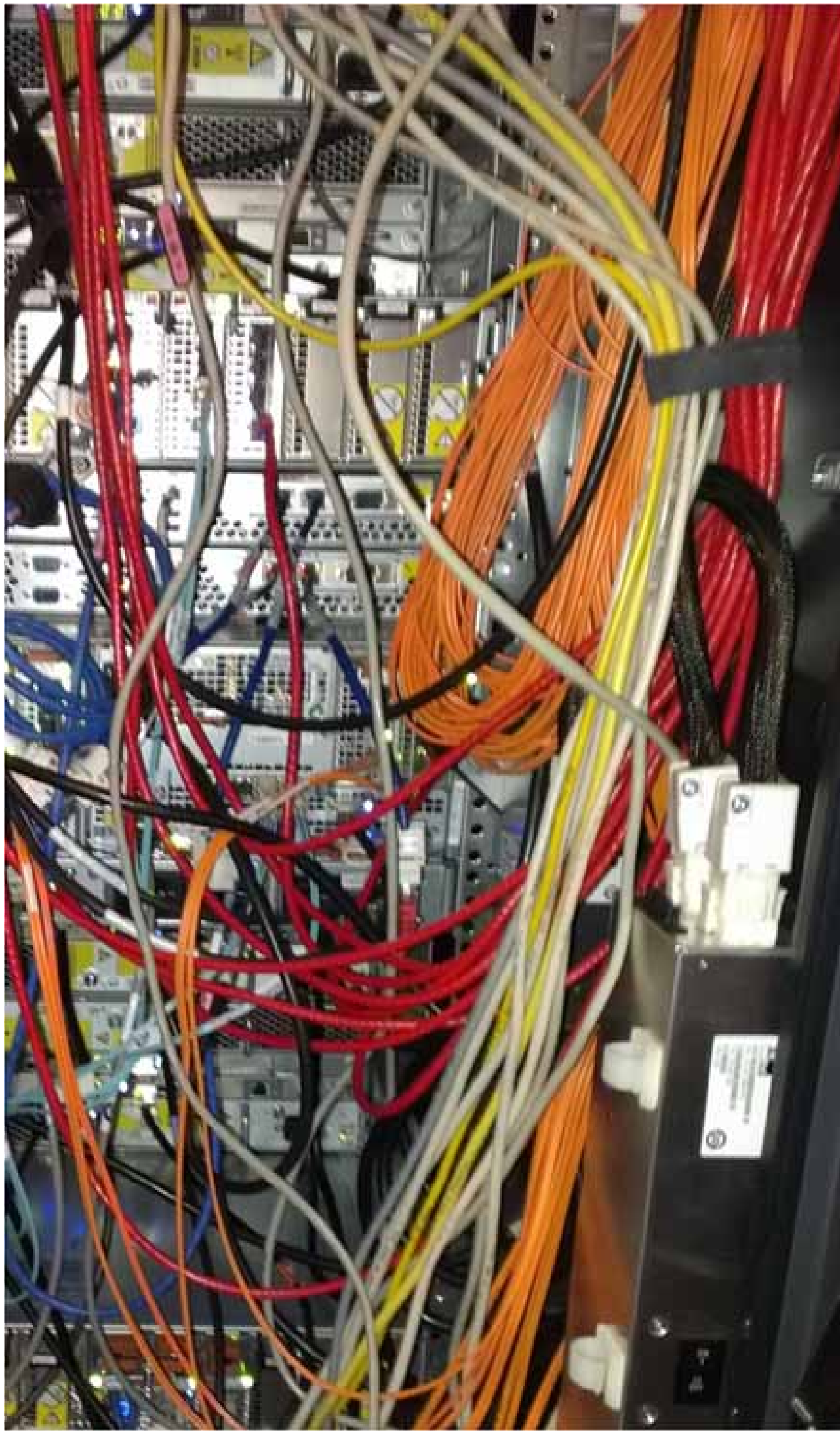




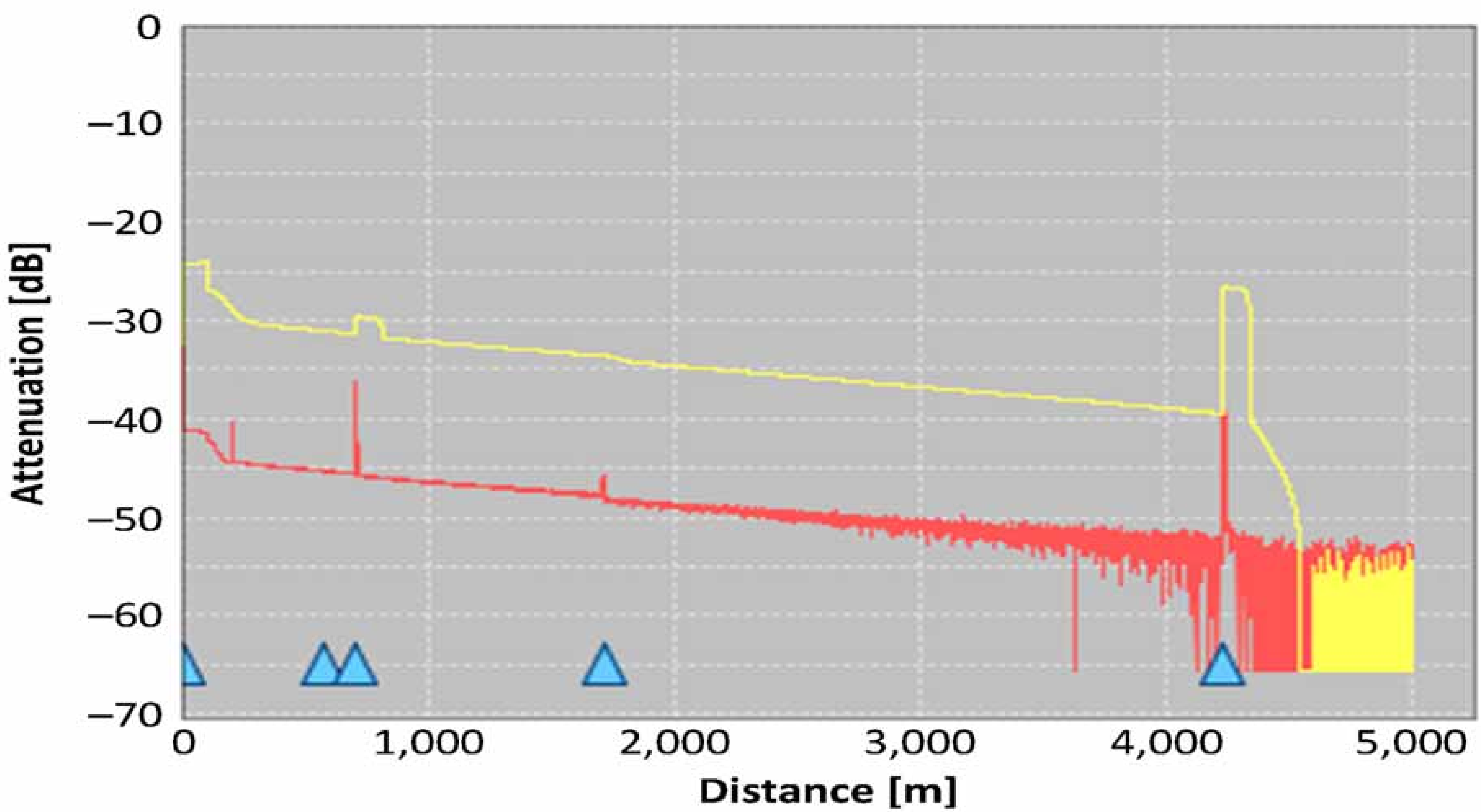


3 to 4.5 dB OSNR improvement

Dirty Patch Cords



OTDR Built into the Raman Card



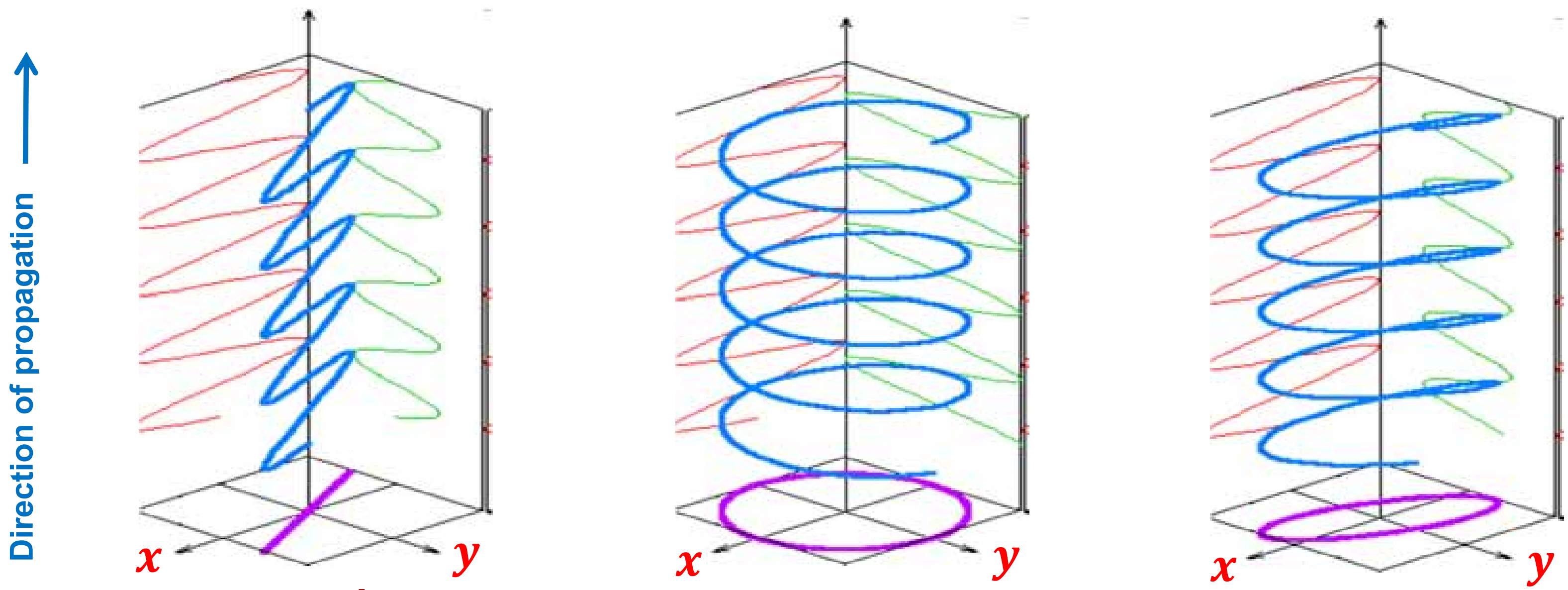
Optical Time Domain Reflectometery (OTDR)

Polarization of Light

Recall an electromagnetic plane wave (light) propagating in free space:

- E-field has components only in directions orthogonal to propagation.
- Such a wave is linearly polarized in the transverse (X/Y) plane.

Sum of plane waves with differing phase results in arbitrary state of polarization.



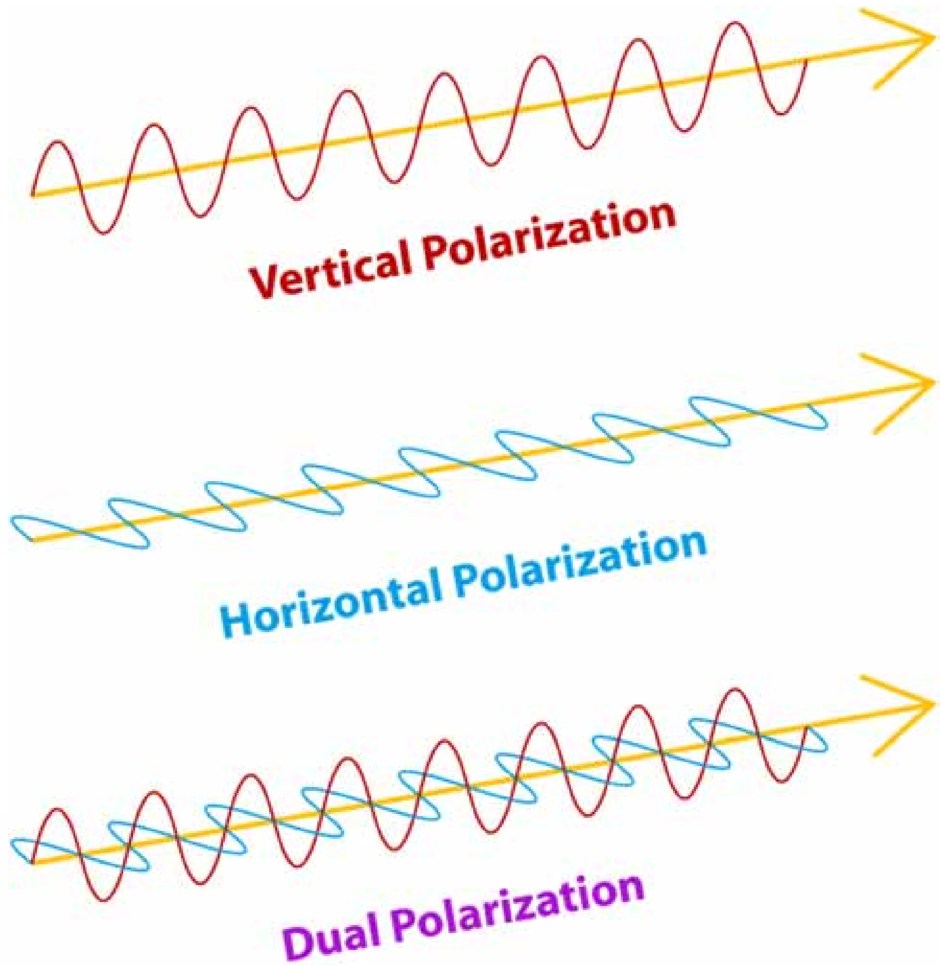
Linear 45-deg.
E-fields in phase

Left/Right Circular:
$\pm\pi/2$ shift

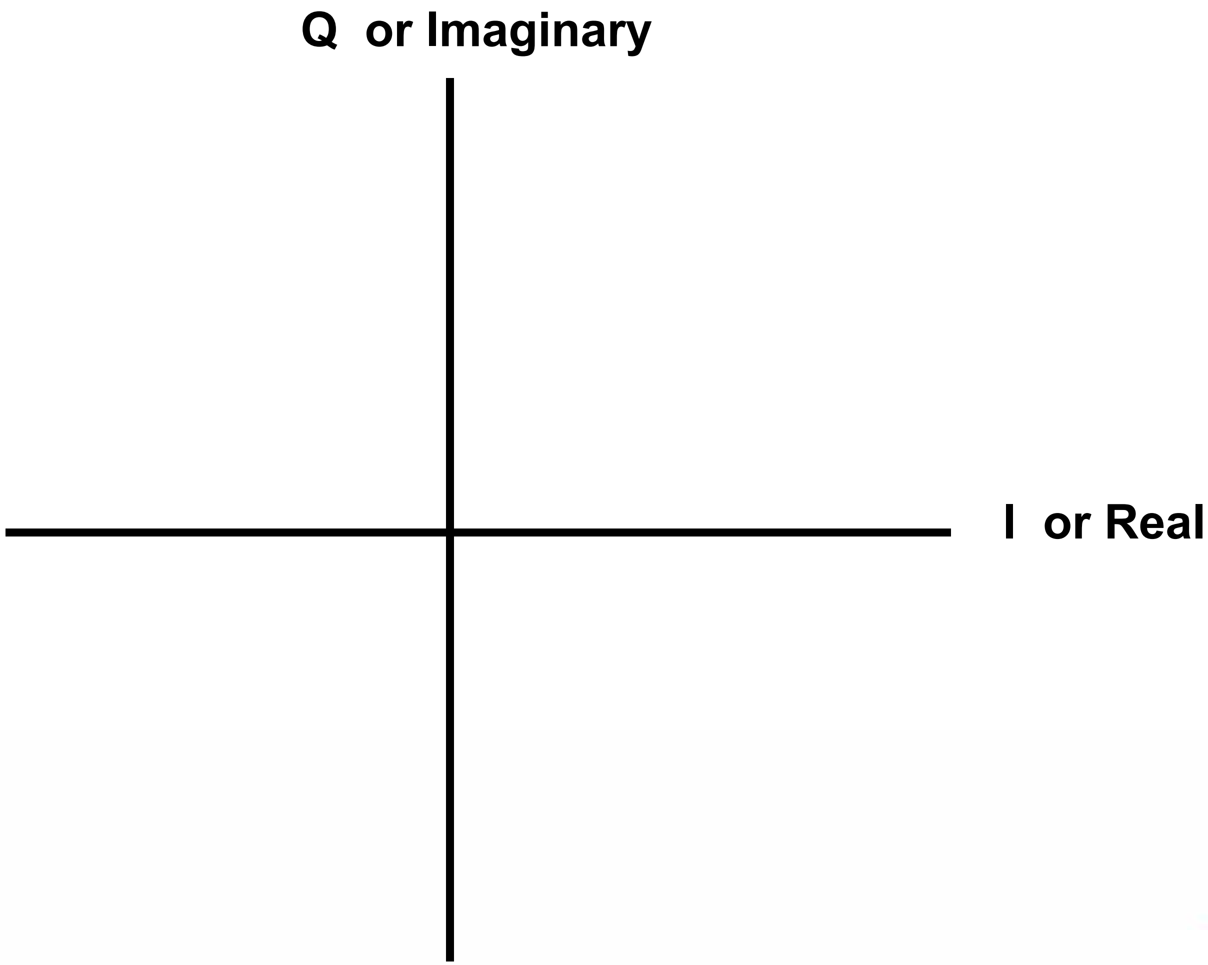
General case:
Elliptical

Figure: Propagation along vertical axis (http://en.wikipedia.org/wiki/Polarization_(waves)))

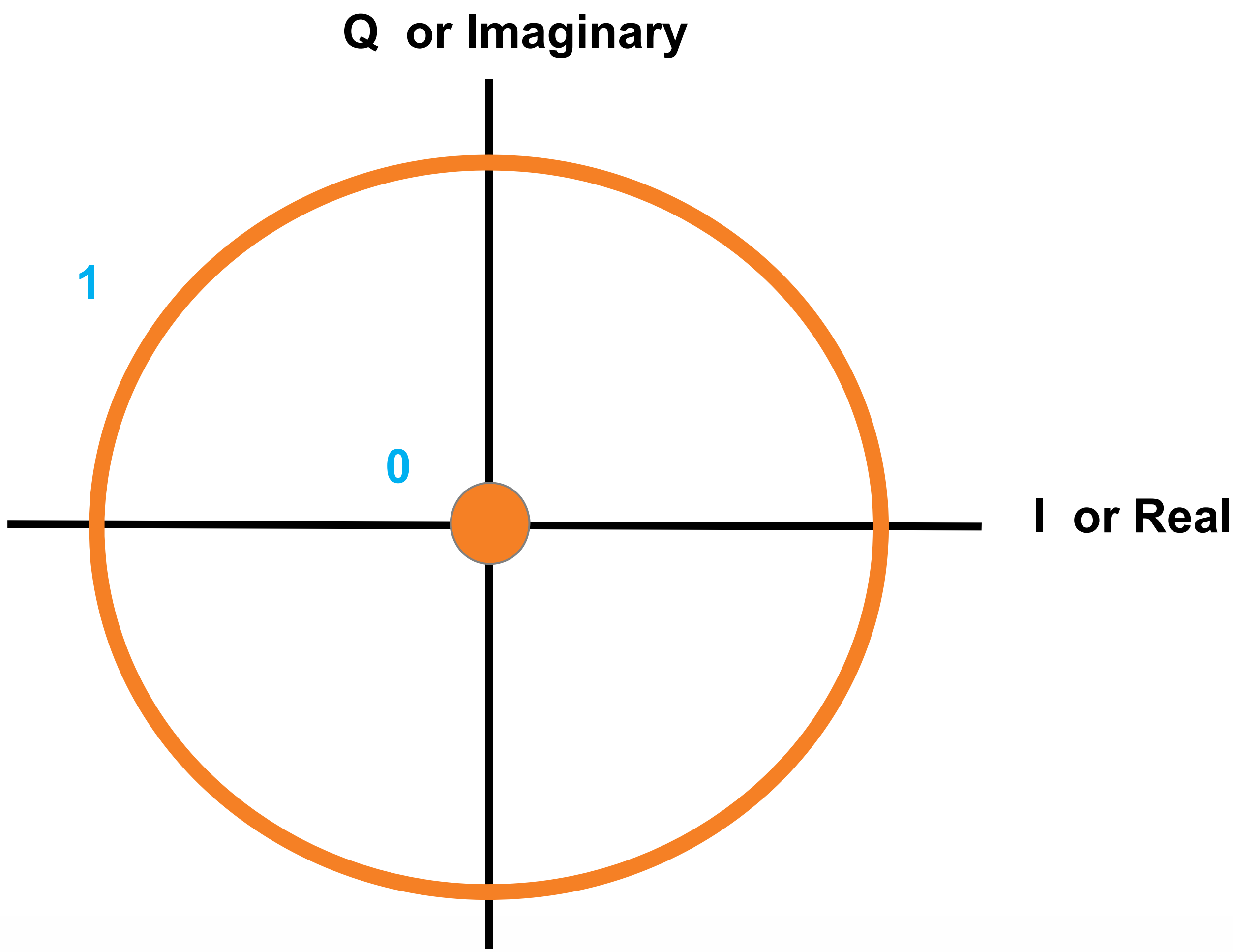
Dual Polarization



Complex Plane of Optical E-field



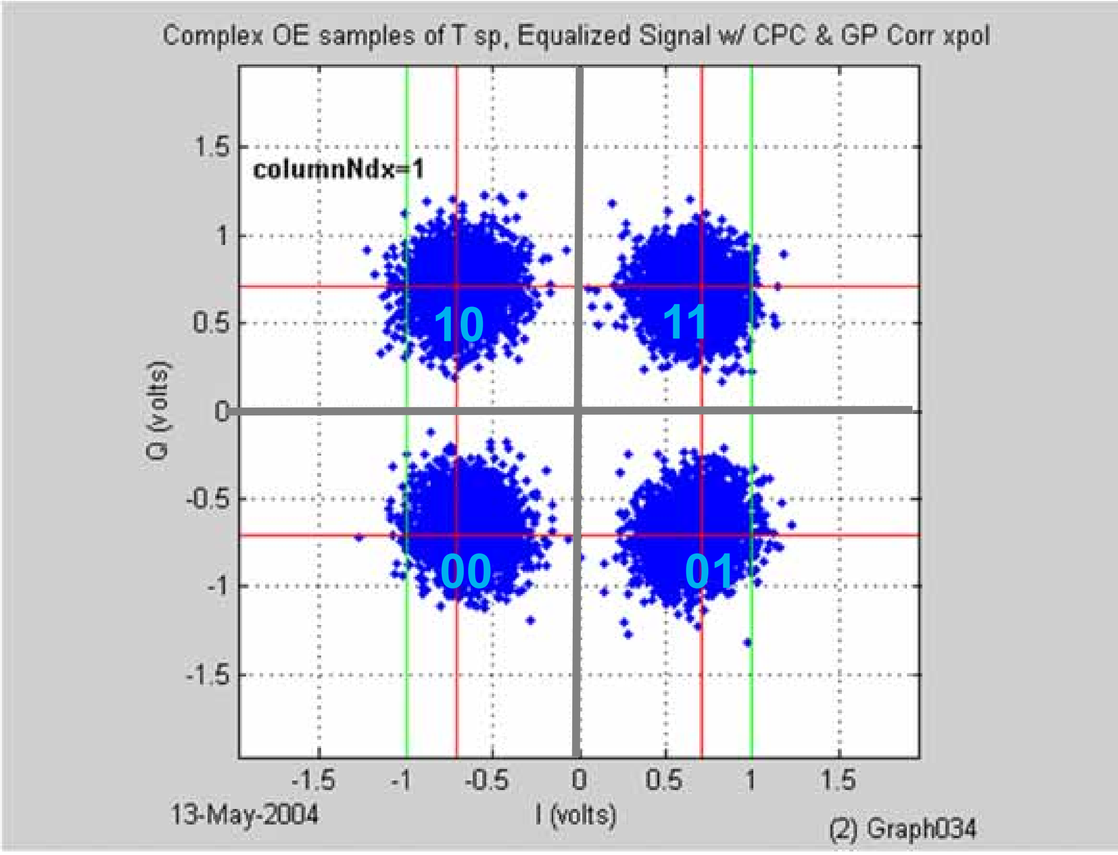
ASK



One bit encoded in the amplitude, per symbol

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

QPSK



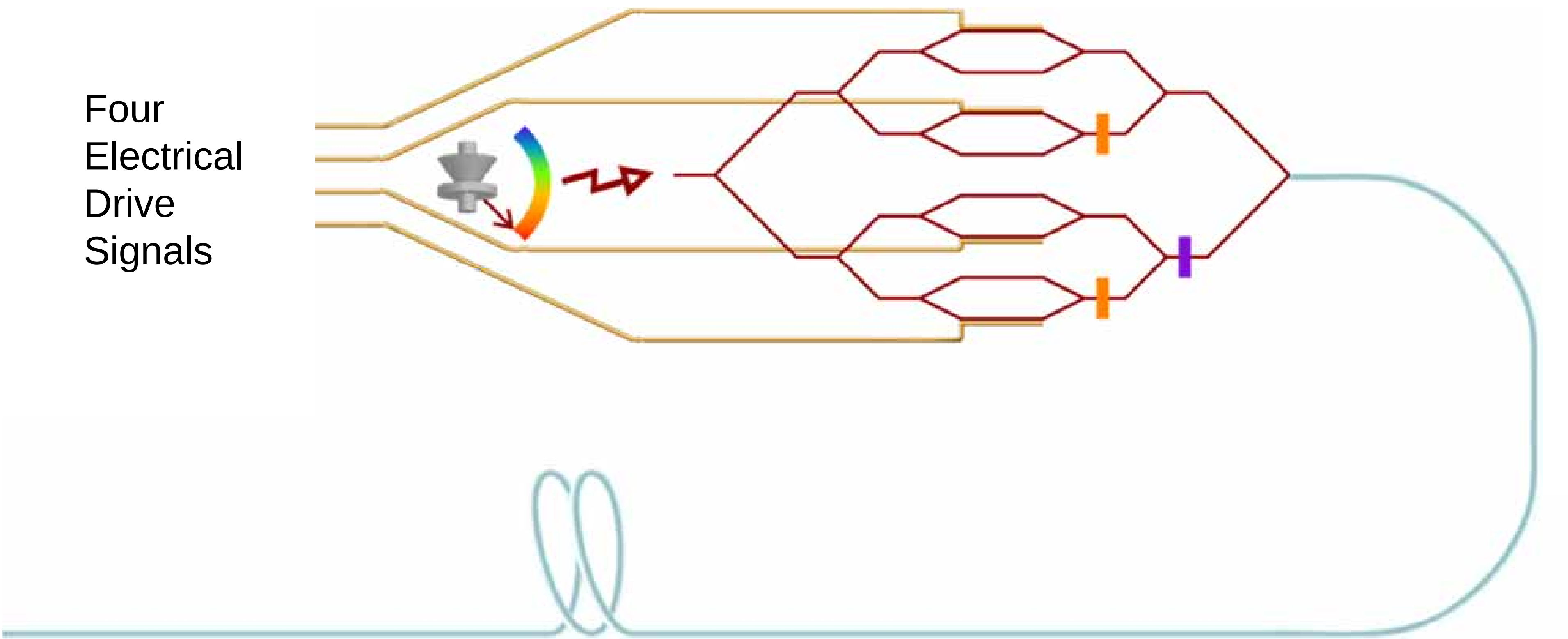
Two bits encoded in the phase, per symbol, per polarization.

4 bits x 10 Gsymbols/second = 40 Gb/s

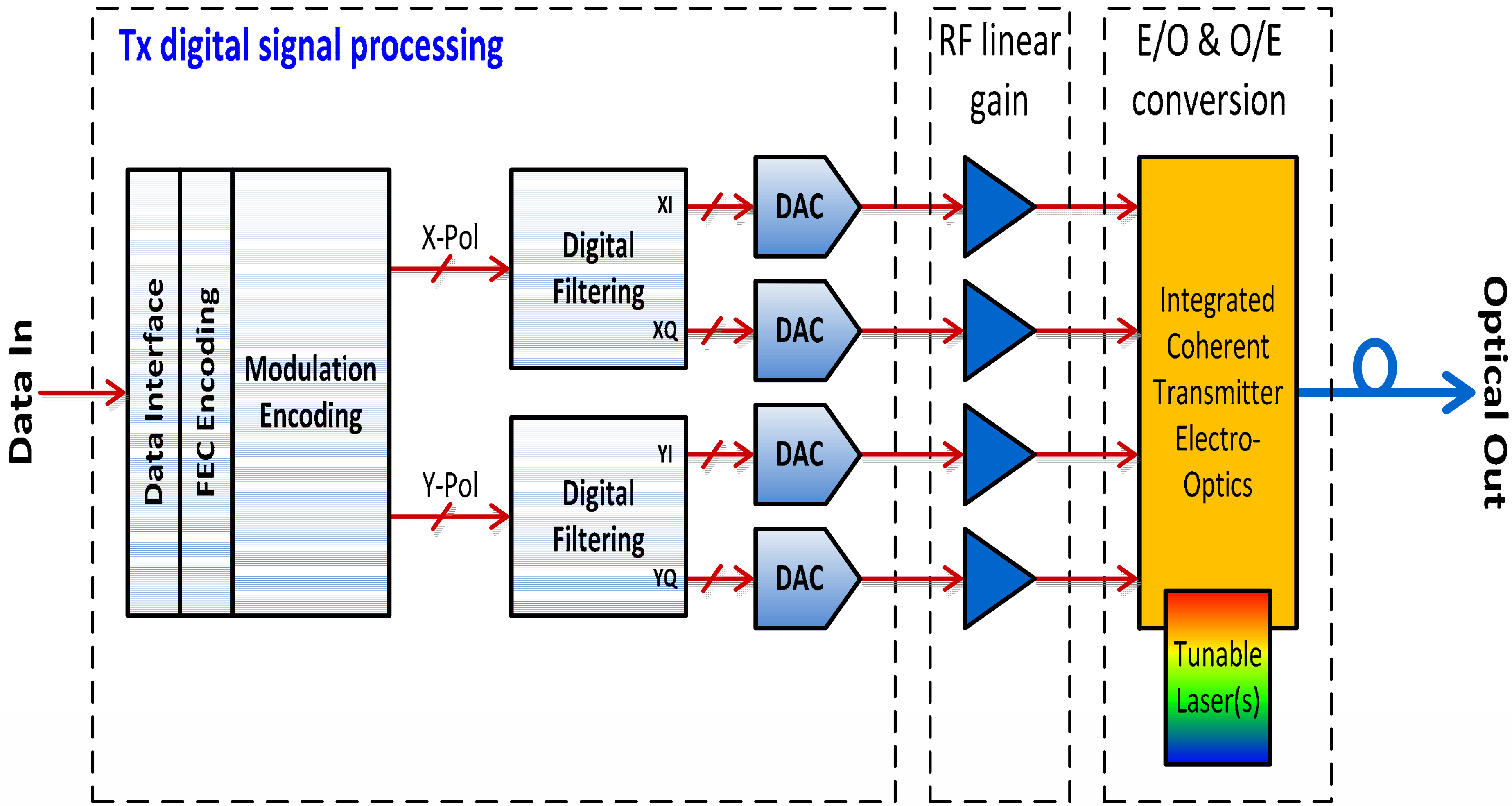
Linear Modulation of E-field

Four
Electrical
Drive
Signals

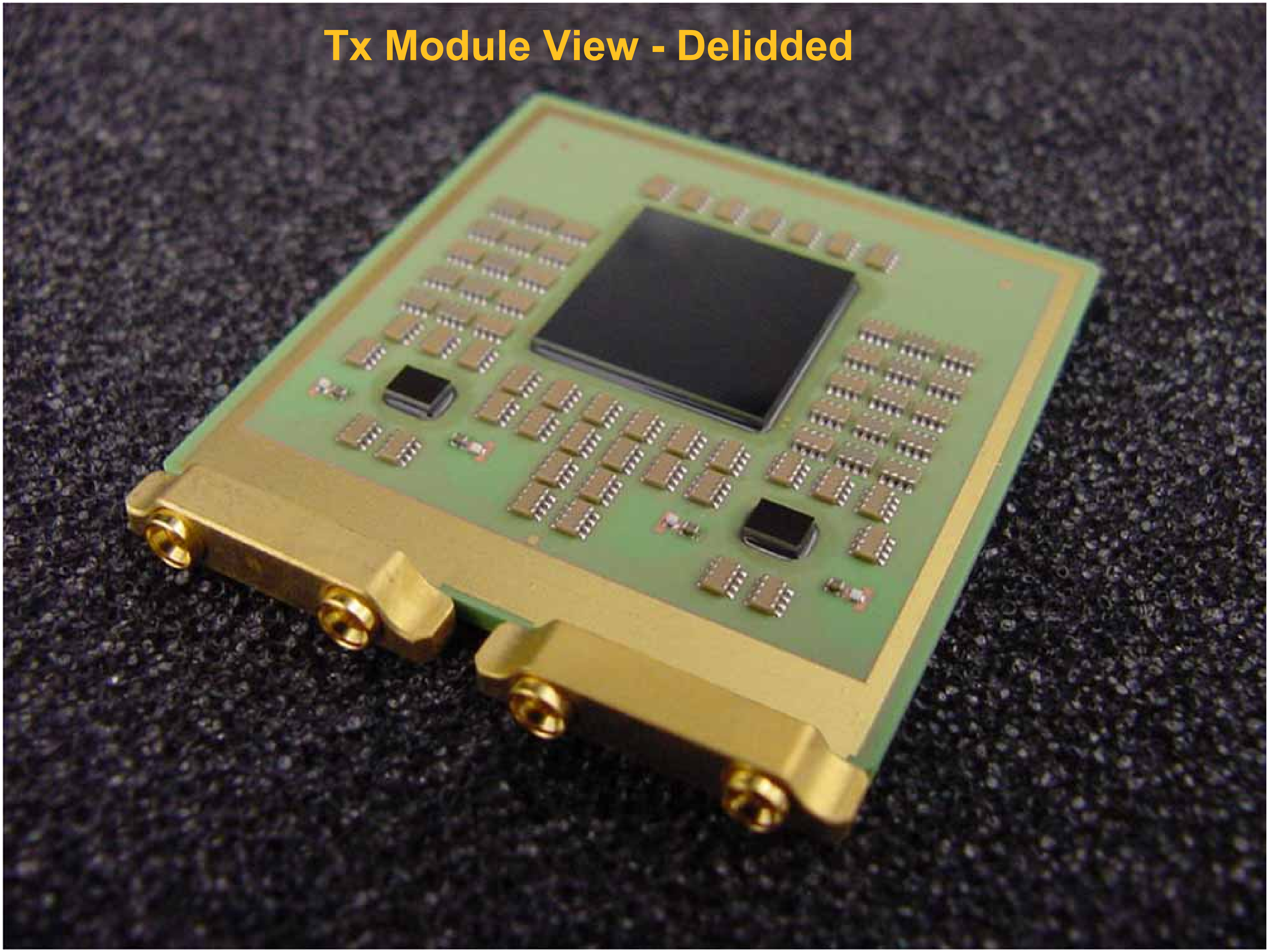
Four
Dimensional
Linear
Modulation



Coherent Transmitter

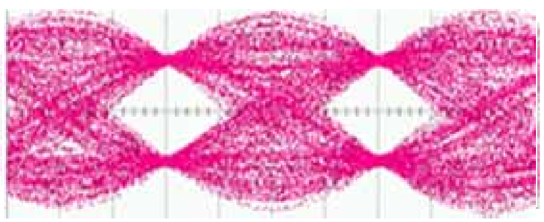


Tx Module View - Delidded



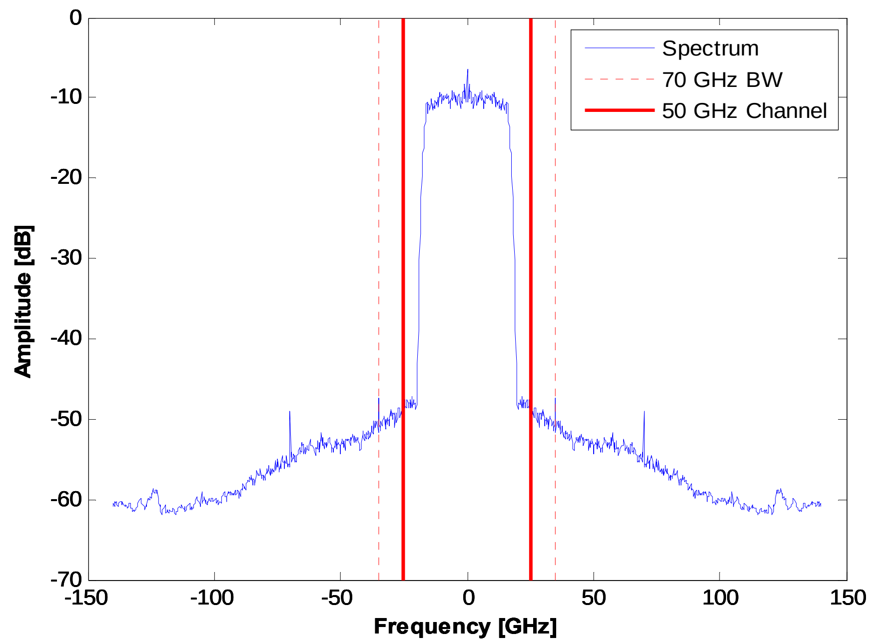
Spectral Shaping

- **Minimize spectral utilization for a given capacity to increase spectral efficiency**
- **DAC technology enables this**



time

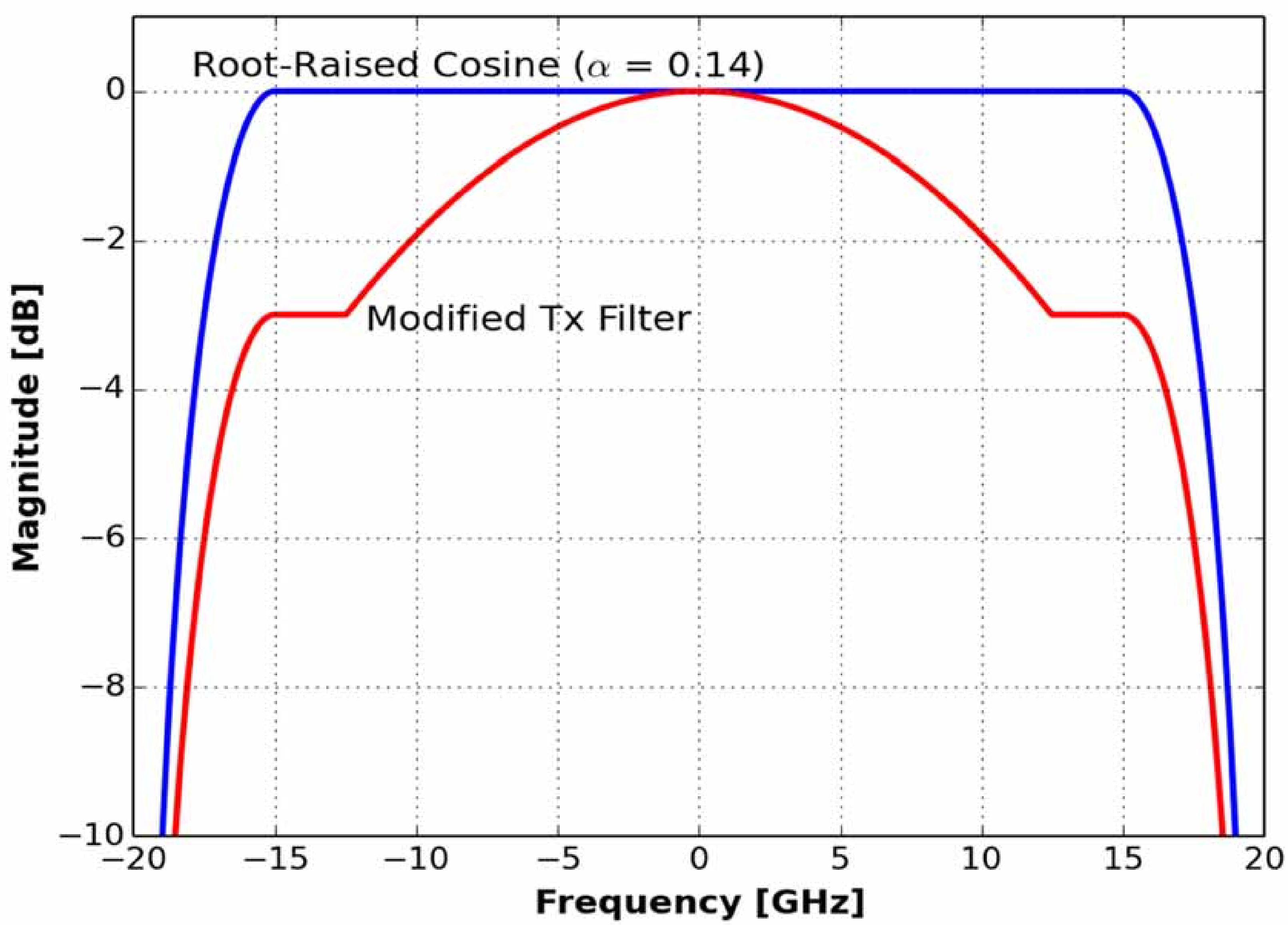
α = 1.0



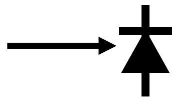
frequency

Alien Wavelength

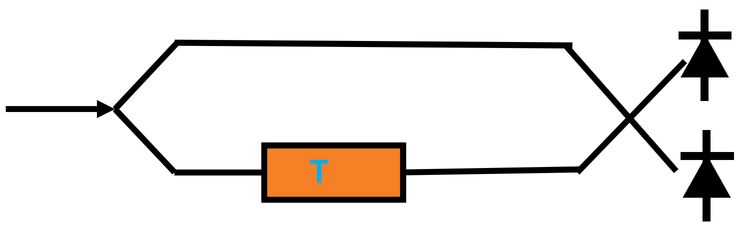
Alien Wavelength



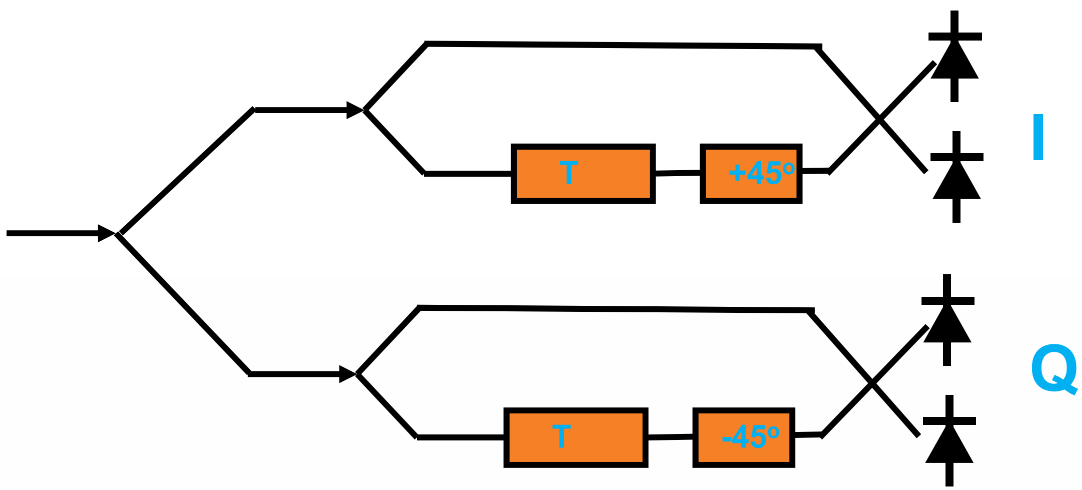
Incoherent Detection



Direct Detection

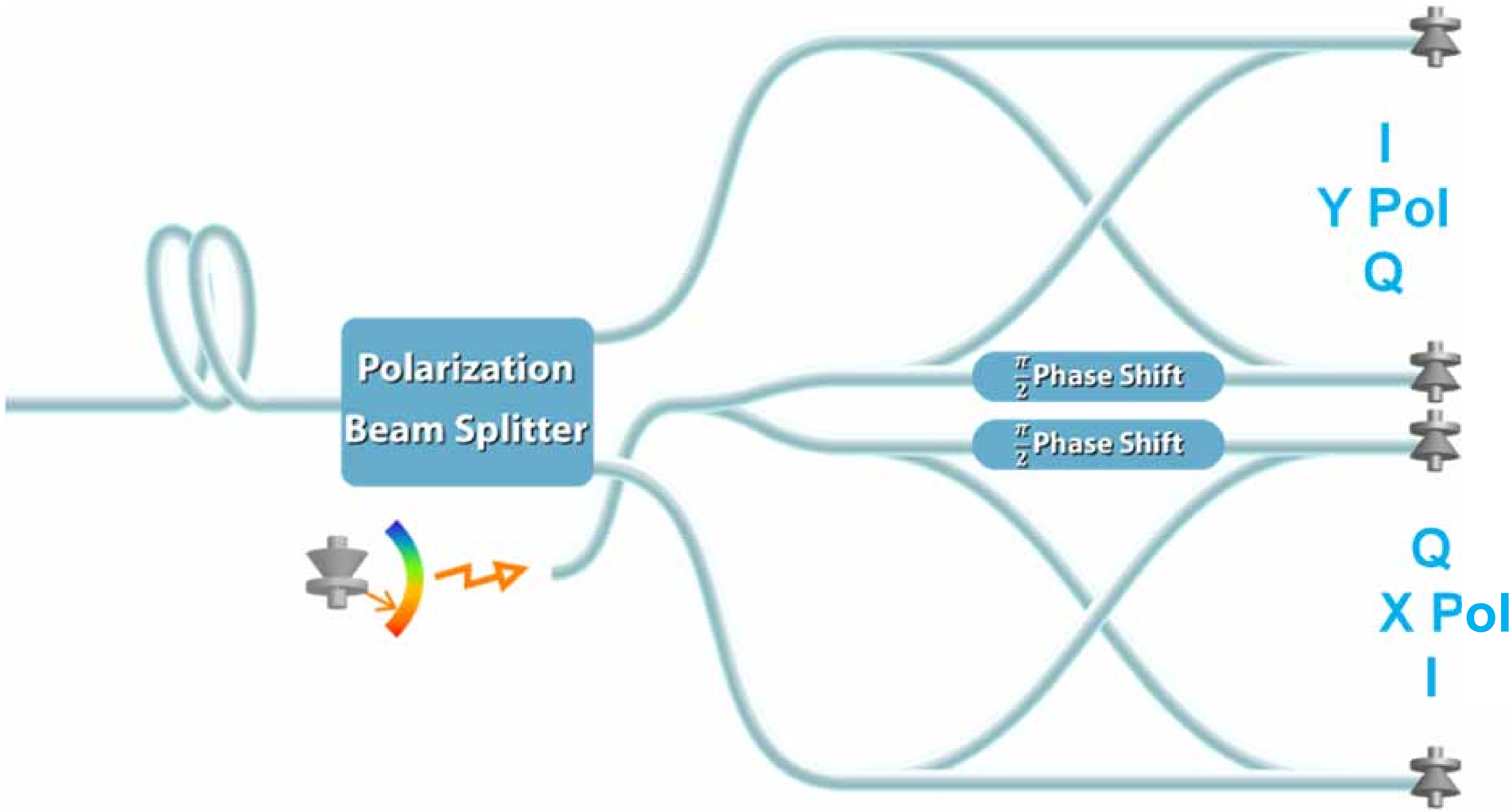


Differential BPSK

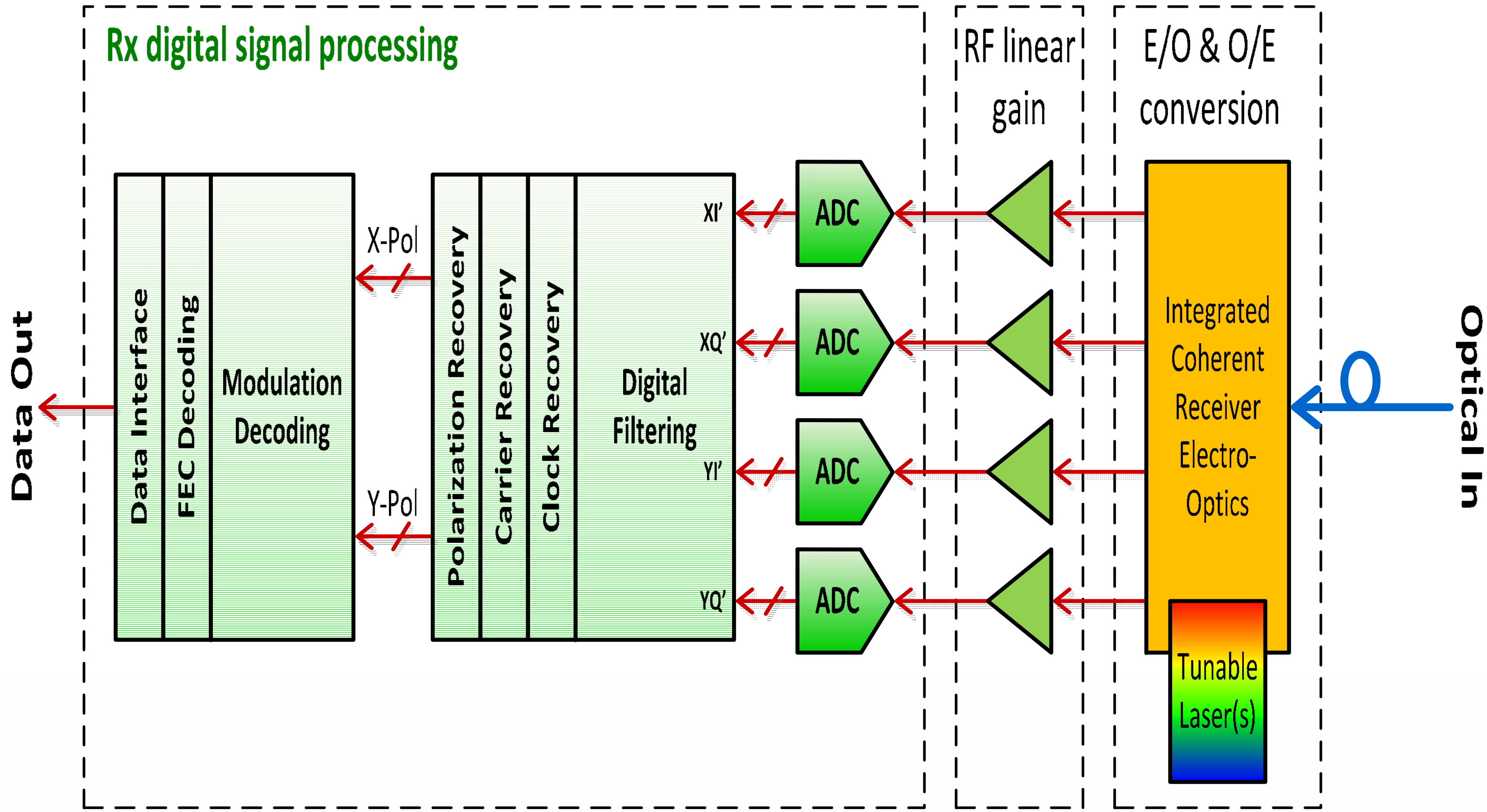


Differential QPSK

Coherent Detection

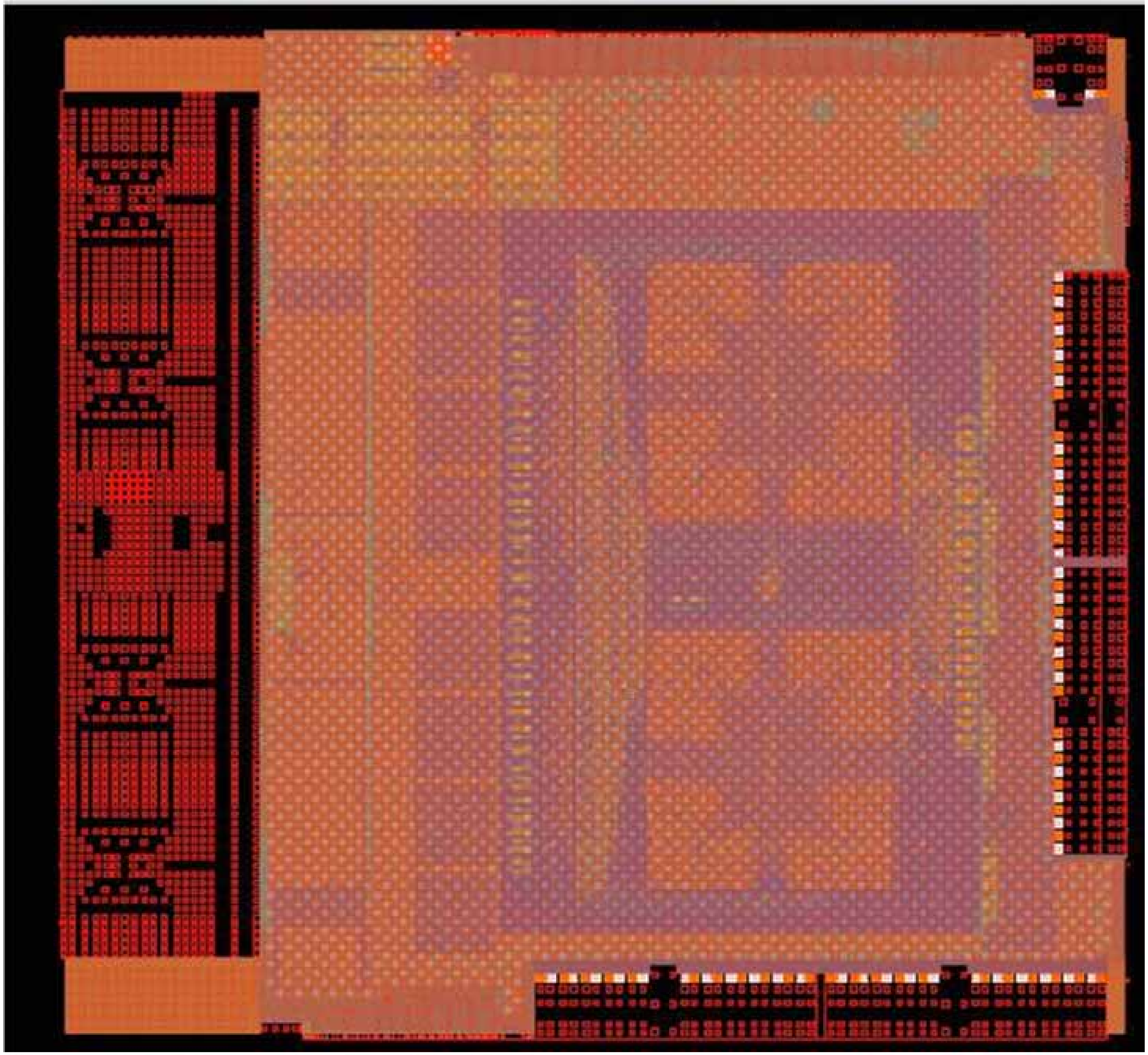


Coherent Receiver



WaveLogic 3 Rx ASIC

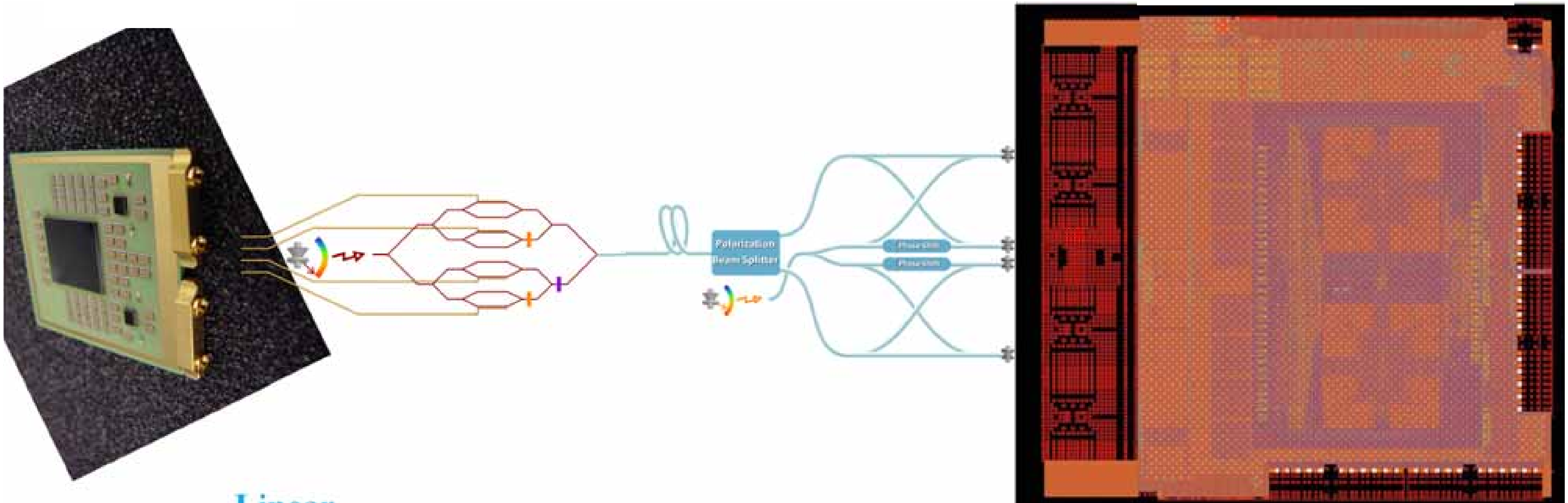
- 70T ops/s
- 32 nm CMOS
- 150M gates
- 3.7 km wire



WaveLogic 3

Tx DSP DAC

ADC Rx DSP

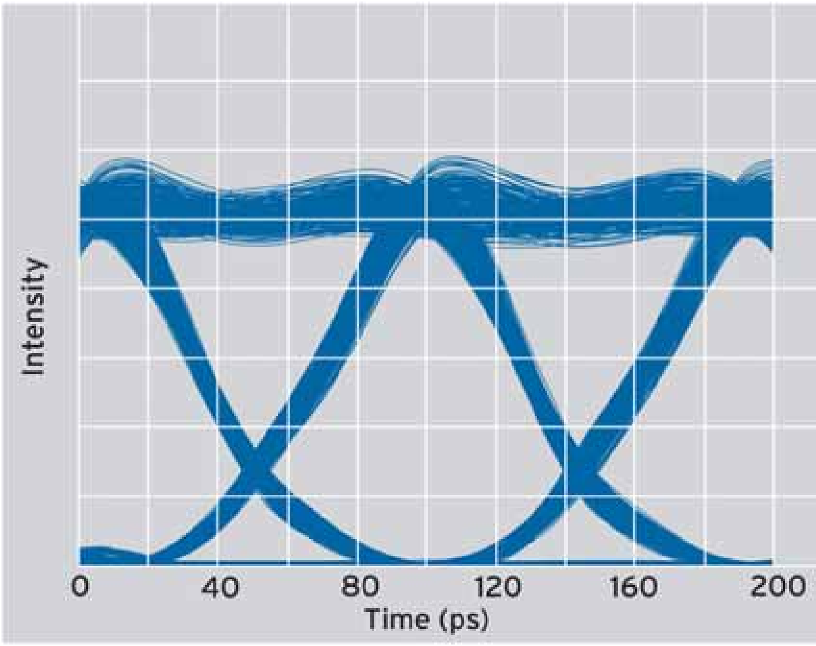


Linear Transducer

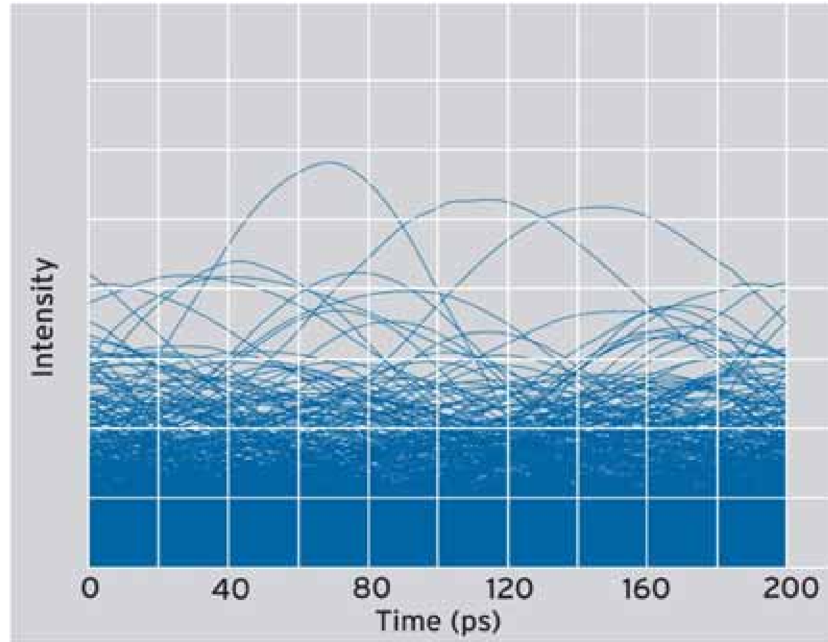
Linear Transducer

WaveLogic 3 Flexible Transceiver

Chromatic Dispersion



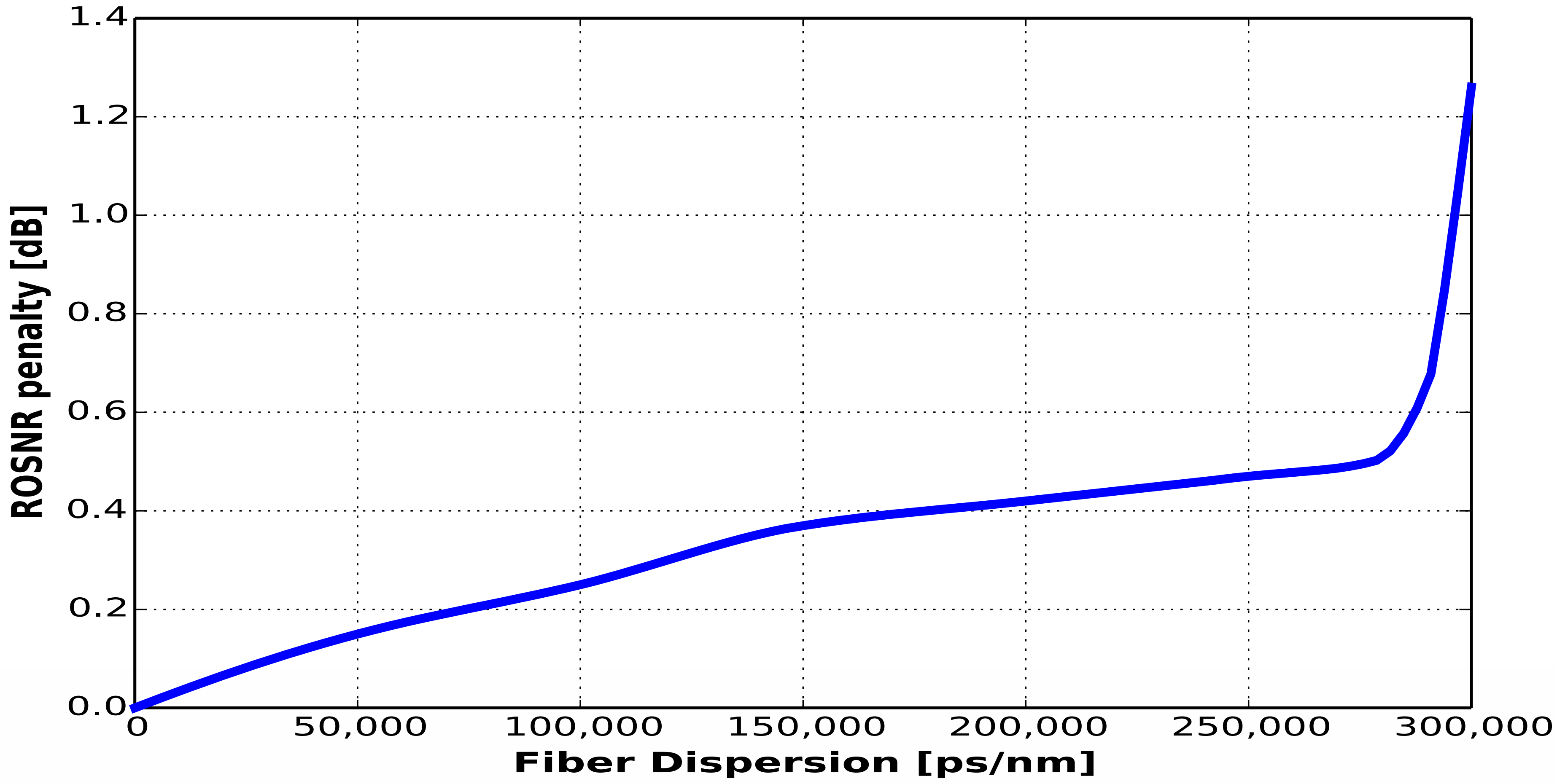
Transmitted Signal



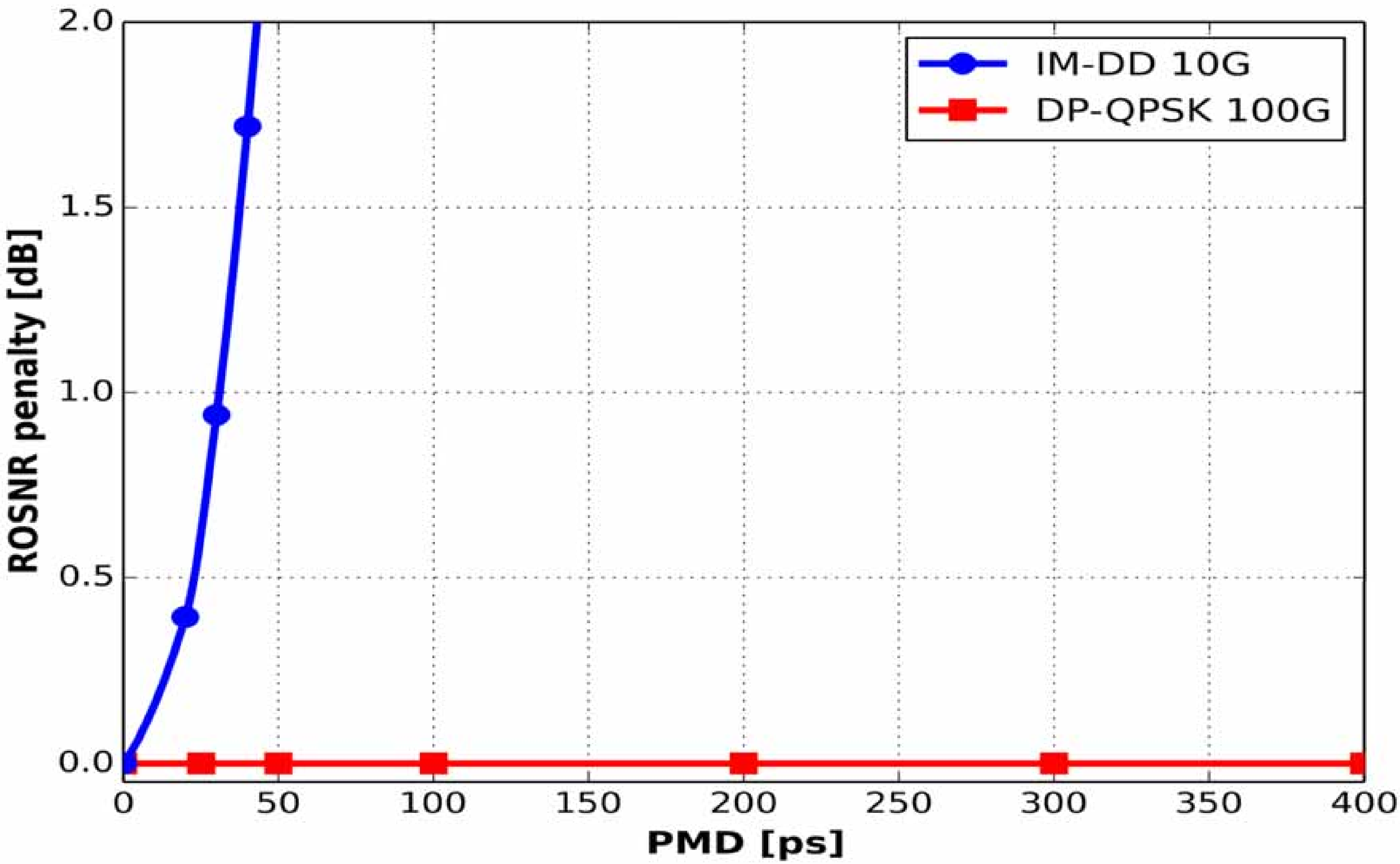
Signal after Dispersion

10G tolerates	**~1000 ps/nm**
Flex-3 tolerates	**300,000 ps/nm**

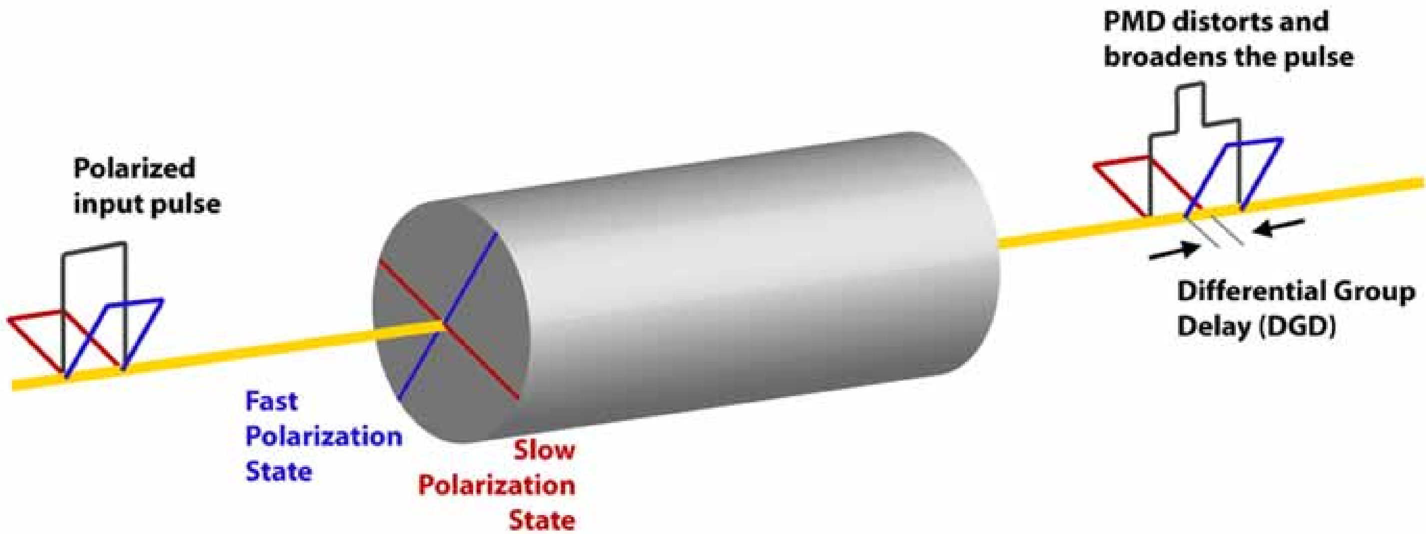
WaveLogic 3 100G Dispersion Tolerance



PMD is Irrelevant with WaveLogic 3

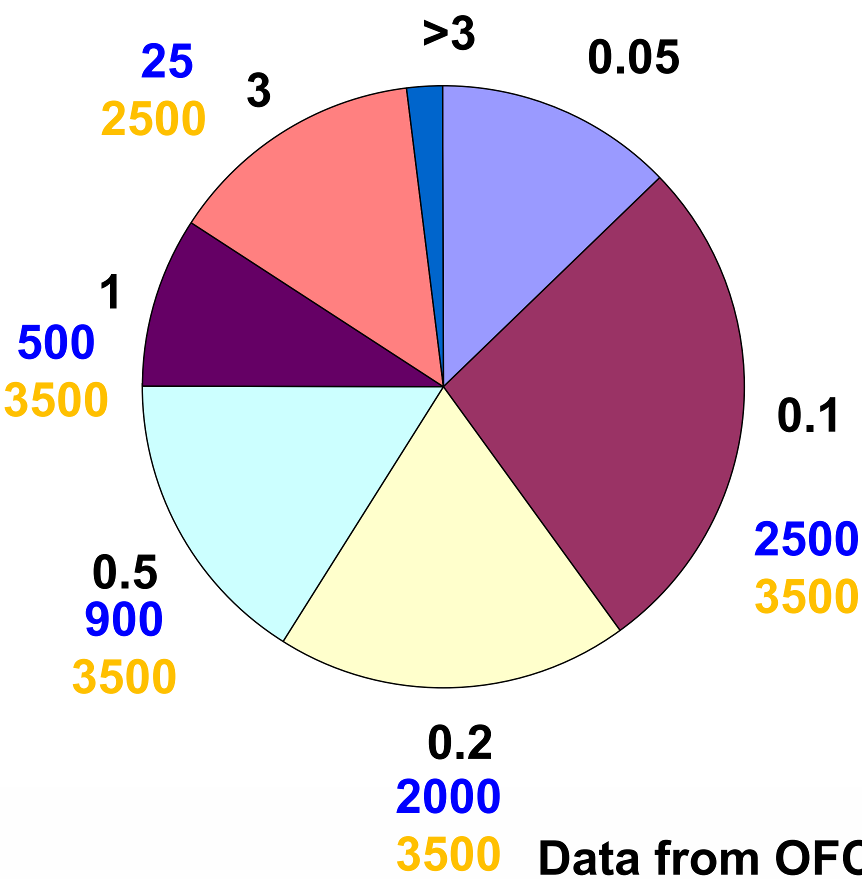


Polarization Mode Dispersion (PMD)



10G tolerates	**15 ps mean**
WaveLogic-3 tolerates	**150 ps mean**

Mean PMD



- 2266 spans of 80 km measured
- Not including concatenation
- Average PMD of 0.75 ps/√km
- Worst = 27.4 ps/√km

Mean PMD in ps/√km
Example 10G Reach
WaveLogic 3 Reach km

Data from OFC 2007 workshop

richard.ednay@ott.co.uk & modesto.morais@iep.pt

Spectral Efficiency

10G allows	10G/50GHz = 0.2 b/s/Hz
Flex-3 allows	400G/80GHz = 5 b/s/Hz

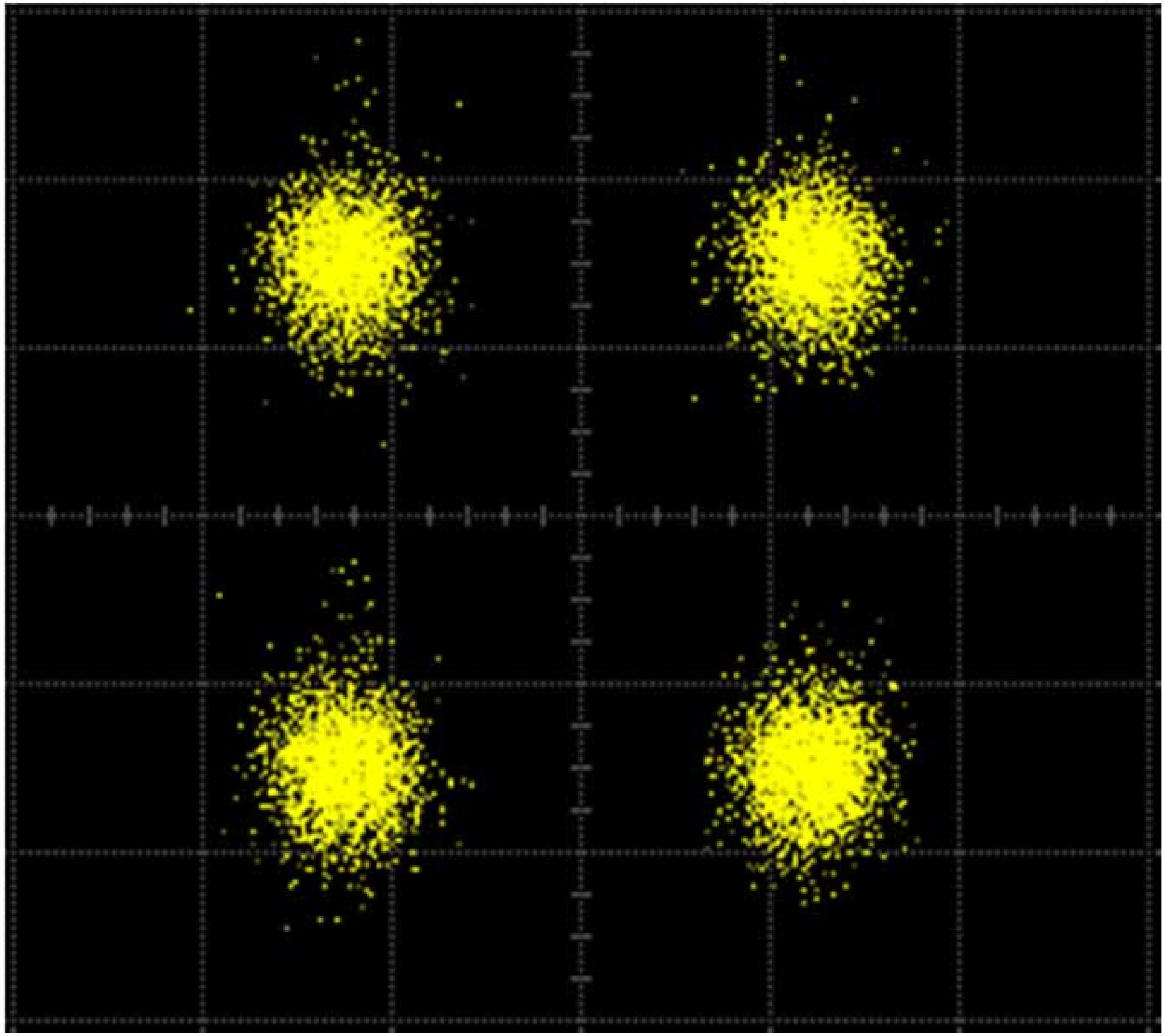
Flexible Latency Soft FEC

	100G	400G
Q-FEC	4 - 35 μs	2 - 18 μs
TX + RX Including Q-FEC	8 - 42 μs	5 - 25 μs

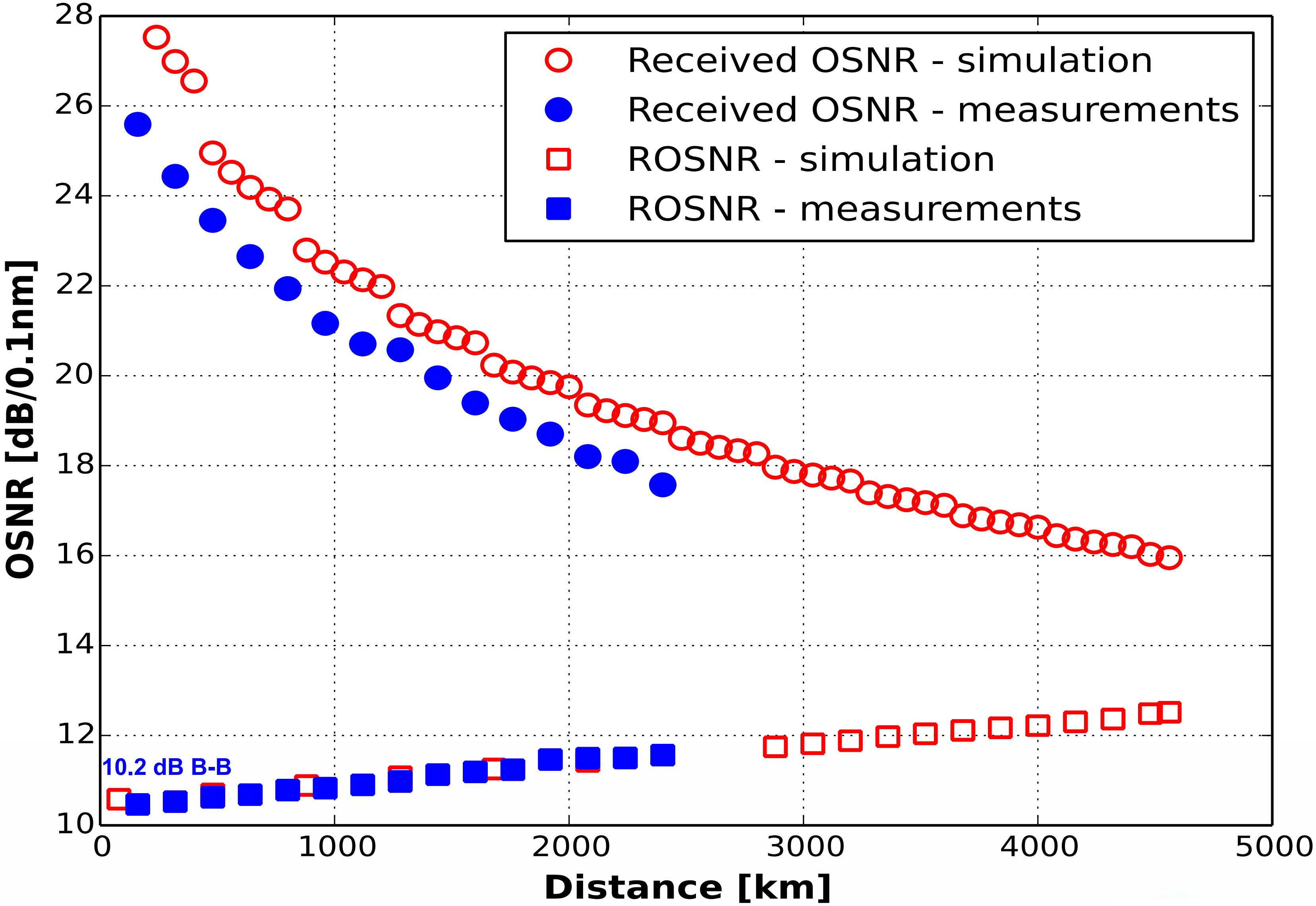
Q-FEC is flexible

- **Latency is provisionable.**
- **Allows tradeoff between performance and latency**

QPSK: 100 Gb/s in 50 GHz



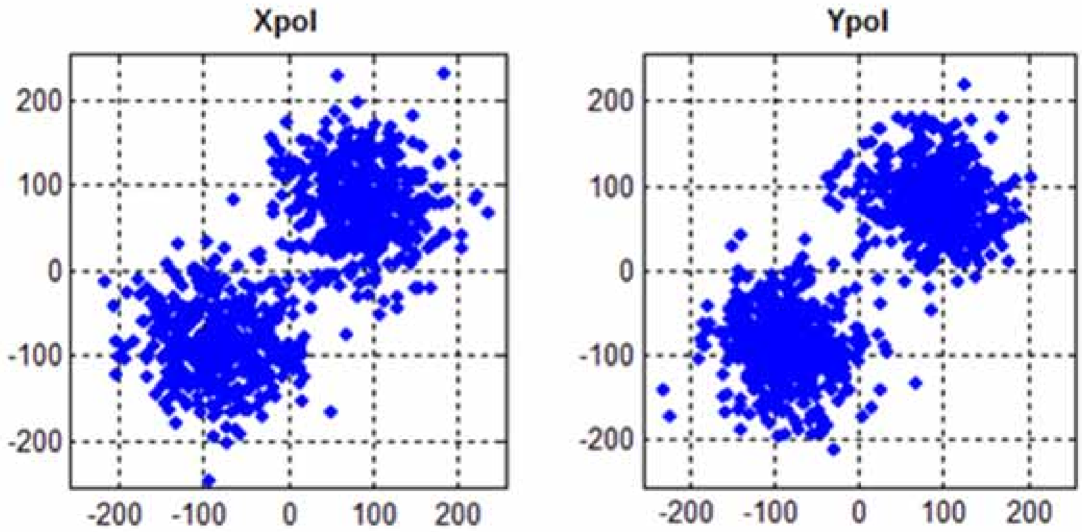
Typical Reach with QPSK

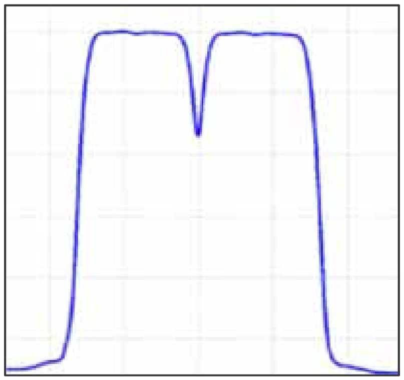


Noise Tolerance

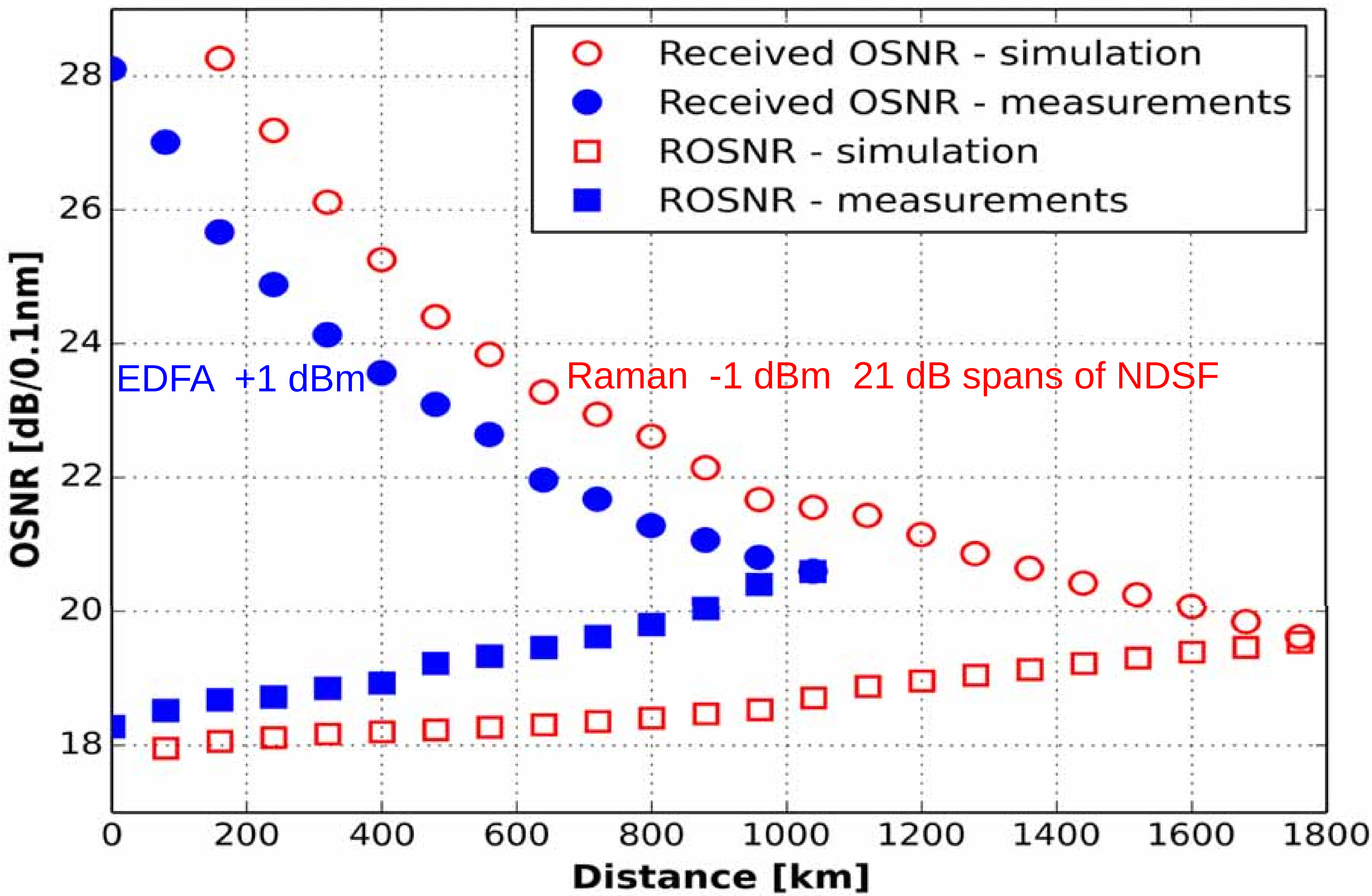
- Tolerance to noise and nonlinearity can be used for reach.
- 3500 km is not always needed!
- The same tolerance gives the ability to handle high loss spans, ROADMs, patch panels, and nonlinear interference.

BPSK: Transpacific Reach on Existing Cables

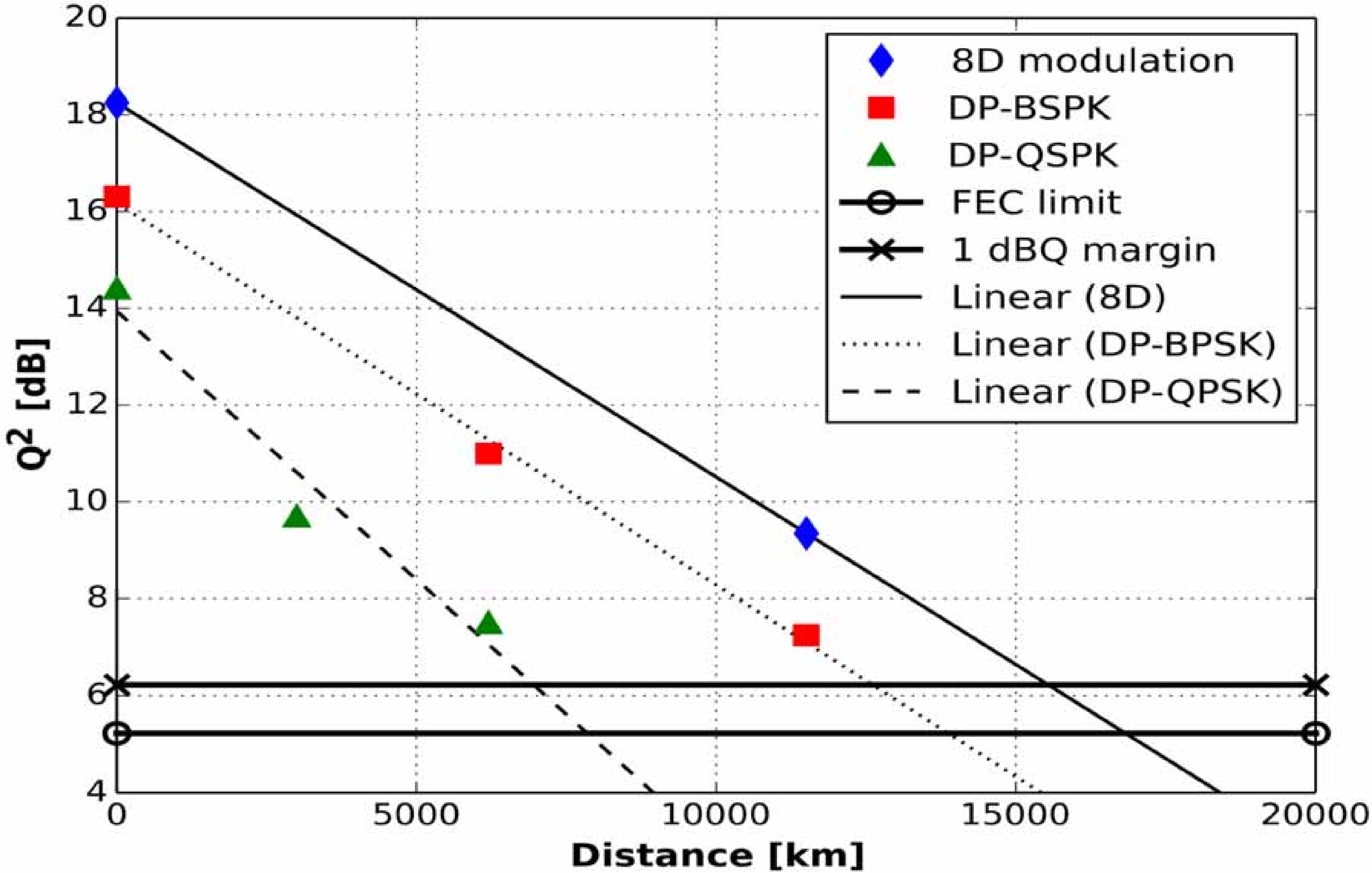




Typical Reach with 16-QAM 400G



Typical Undersea Reach



Flexible Transciever

Received Constellation, X-Polarization

Received Constellation, Y-Polarization

- 35 Gbaud, captured from Rx after 300 km
- Production WaveLogic 3 Hardware
- Firmware by Ian Roberts
- 10GE test set; traffic daisy-chained
- Error Free, even during transitions