THE POSSIBILITIES ARE INFINITE FUJITSU

40Gb/s & 100Gb/s Transport in the WAN

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Outline

- Introduction
- Challenges of 40Gbps transmission
- Modulation formats for 40Gbps
- Advanced optical technologies enabling 40Gbps
- From 40Gbps to 100+Gbps
- Summary

Introduction

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- **Today's networks deploy 2.5Gbps and 10Gbps line rates**
- **Networks will migrate to 40Gbps (and in the future to 100Gbps) per wavelength**
  - High demand for transmission capacity
  - Higher rate client interfaces
- **Technologies to support 40Gbps transmission**
  - Advanced modulation format
  - Tunable Chromatic Dispersion Compensator (TDC)
  - Tunable lasers
- **40Gbps networks must co-exist with today's networks**

Supporting 40Gbps Transmission

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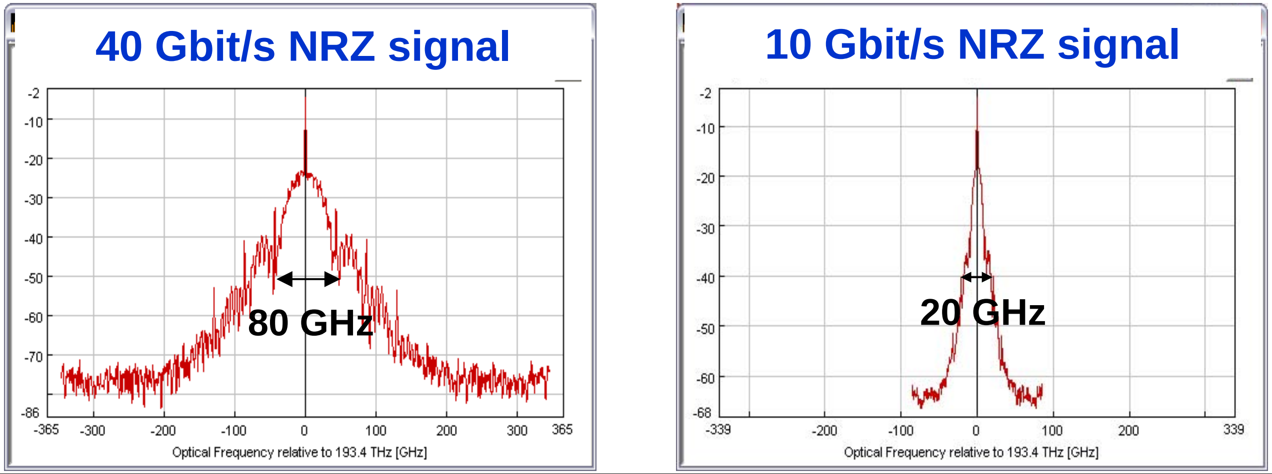
Same transmission quality as 10Gbps systems

- Challenges associated with 40Gbps solution:
  - OSNR requirement increases by 6 dB
  - Chromatic dispersion tolerance decreases (1/16-th of 10G system)
  - PMD tolerance decreases (1/4-th of 10G system)

Same network connectivity as 10Gbps

- Challenges:
  - Sensitivity to OADM filtering increases

Example of optical spectra



Increasing Channel Capacity

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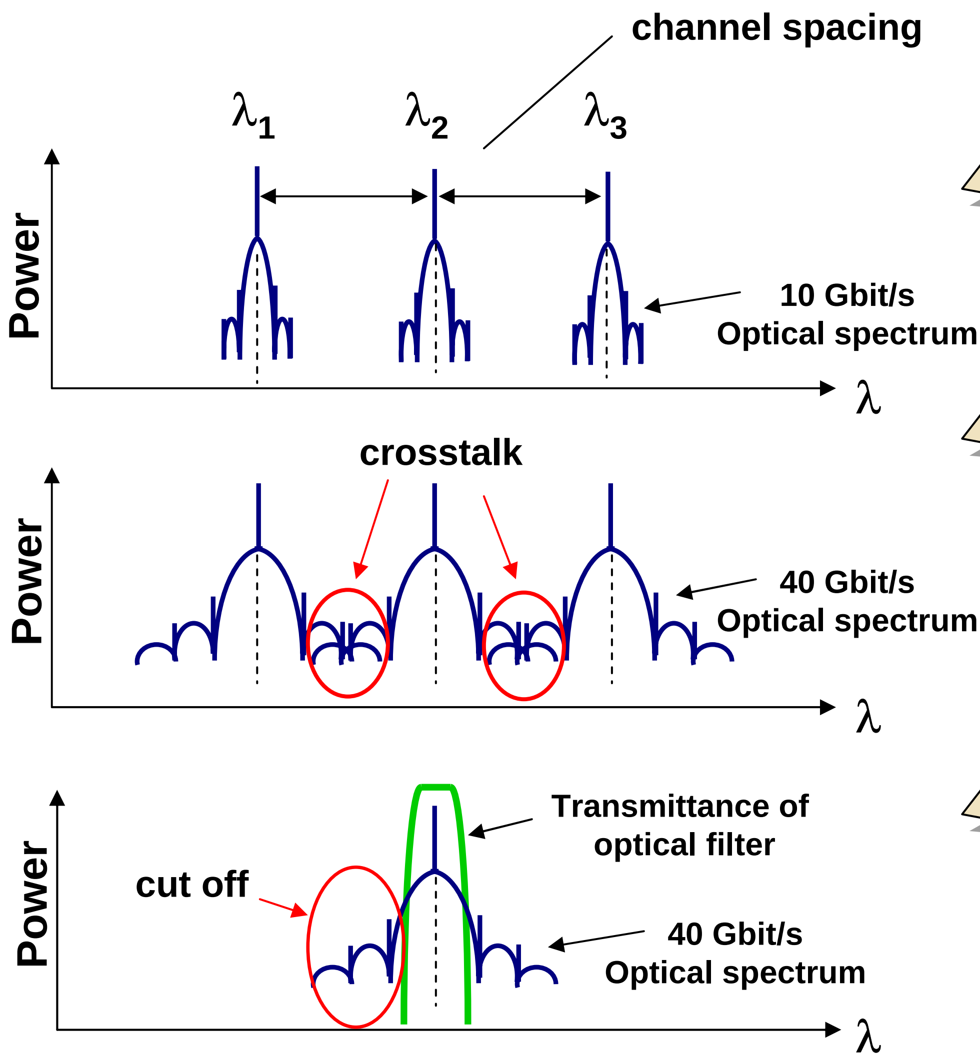

- **3 channels at 10 Gbit/s Channel spacing: Δλ**
- **3 channels at 40 Gbit/s Channel spacing: Δλ (same)**
  - Crosstalk between channels
- **Spectrum degradation due to cascaded ROADM filter devices**

Solution: New Modulation Formats with improved spectral efficiency.

Light Properties to Modulate

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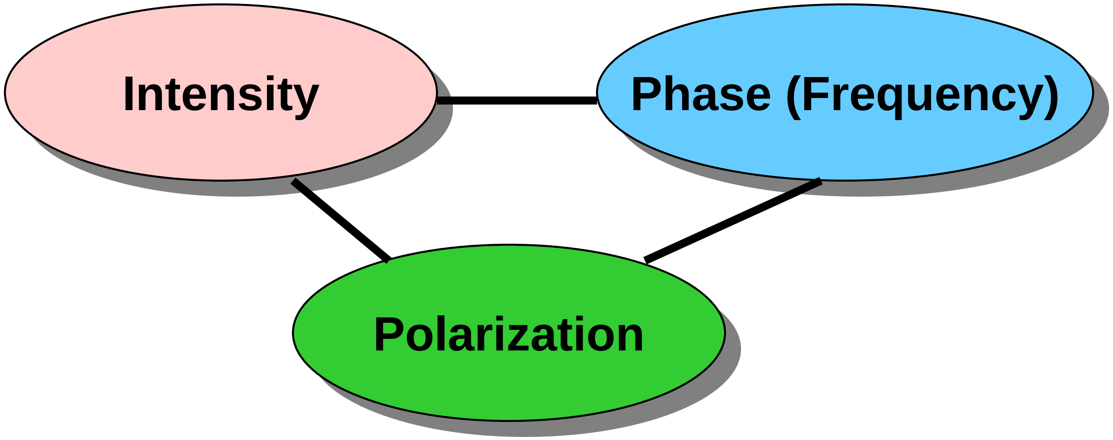
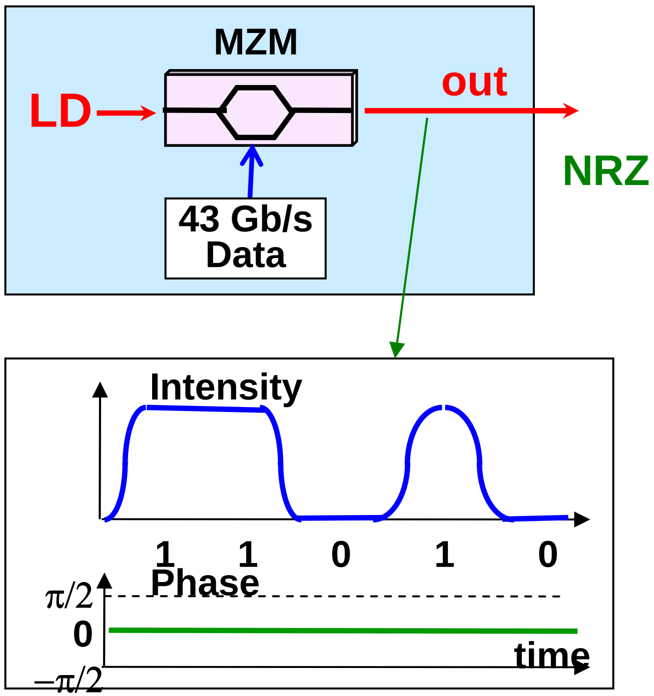


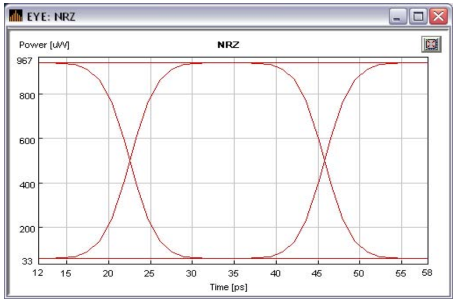
- **Modulate one or more light properties**
  - Intensity modulation (on-off keying):
    - Widely used modulation technique for up to 10Gbps transmission
      - Easy to modulate and easy to detect
  - Phase modulation:
    - Well known technique but was not used in optical communications
      - Detection is more difficult compared to on-off keying
  - Polarization modulation:
    - Relatively new technique
      - Detection is difficult

Non Return-to-Zero (NRZ)

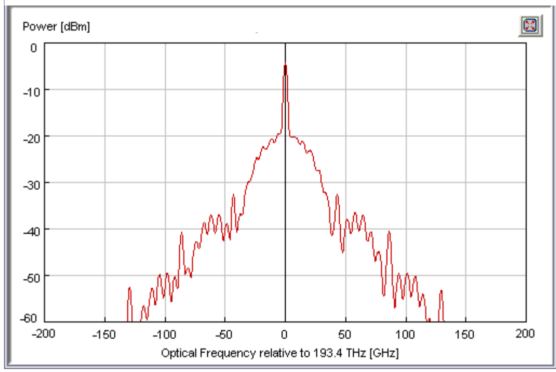
Transmitter



Eye diagram



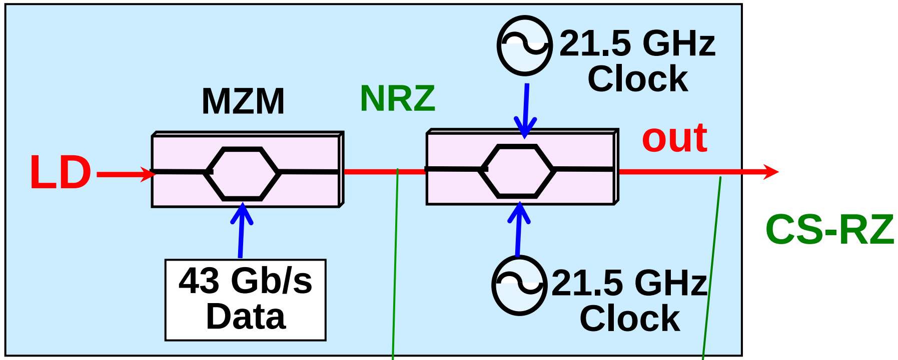
Optical spectrum



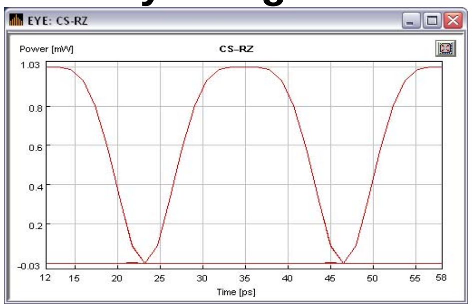
- Intensity modulation format
- Widely used at 10Gb/s
- Simplest Tx and Rx configuration
- The optical spectrum has a carrier
- NRZ has medium width optical spectrum

Carrier-Suppressed Return-To-Zero (CS-RZ)

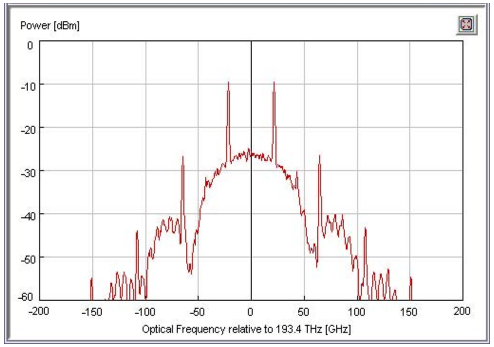
Transmitter

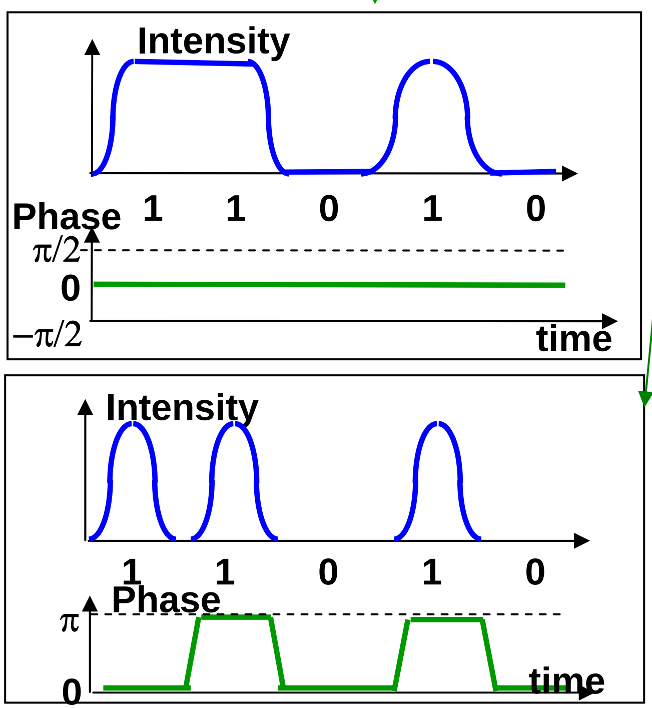


Eye diagram



Optical spectrum



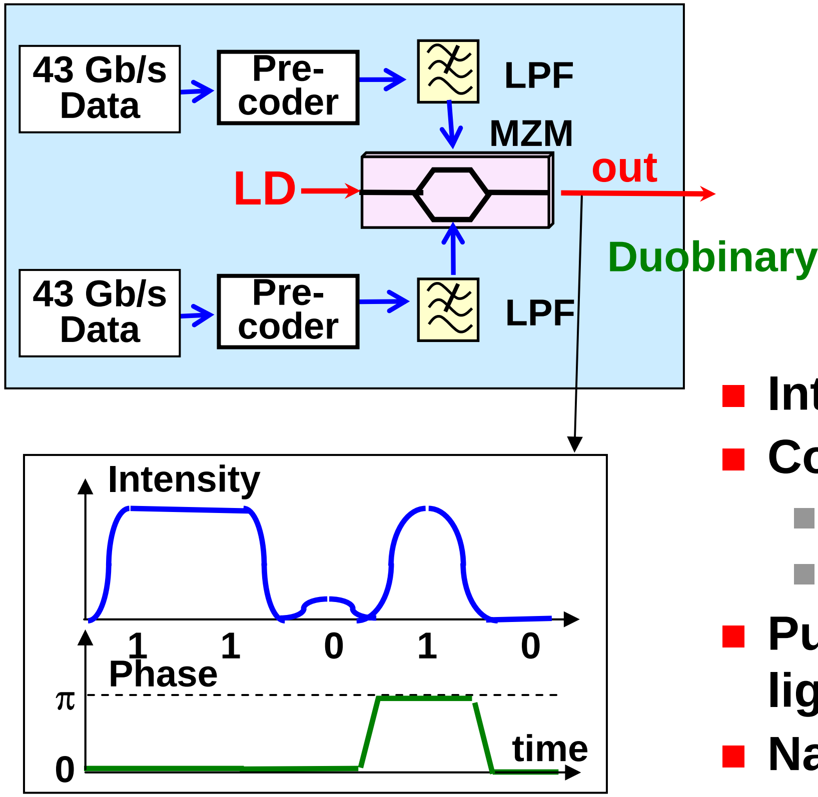


- **Intensity modulation format**
- **CS-RZ Tx requires additional clock modulation**
- **Pulse train has RZ shape with alternate π phase shifts between consecutive bit slots**
- **The optical spectrum has a suppressed carrier**
- **High tolerance to non-linear effects**
- **Higher receiver sensitivity than NRZ**

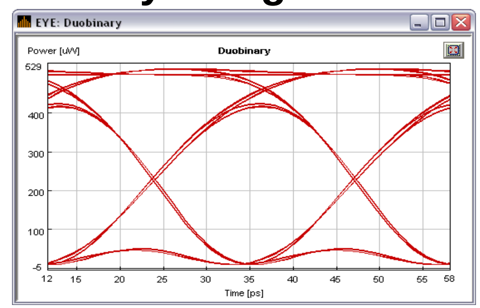
Y. Miyamoto *et al.*, in Proc. OAA'99, vol. PdP4, 1999.

Duobinary Modulation Format

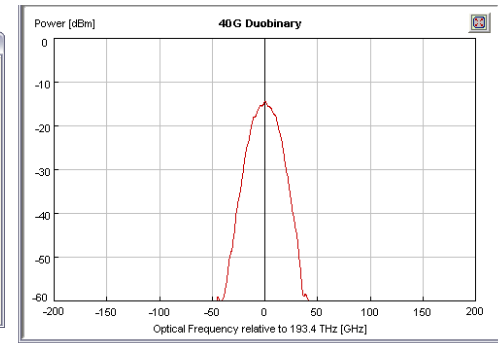
Transmitter



Eye diagram



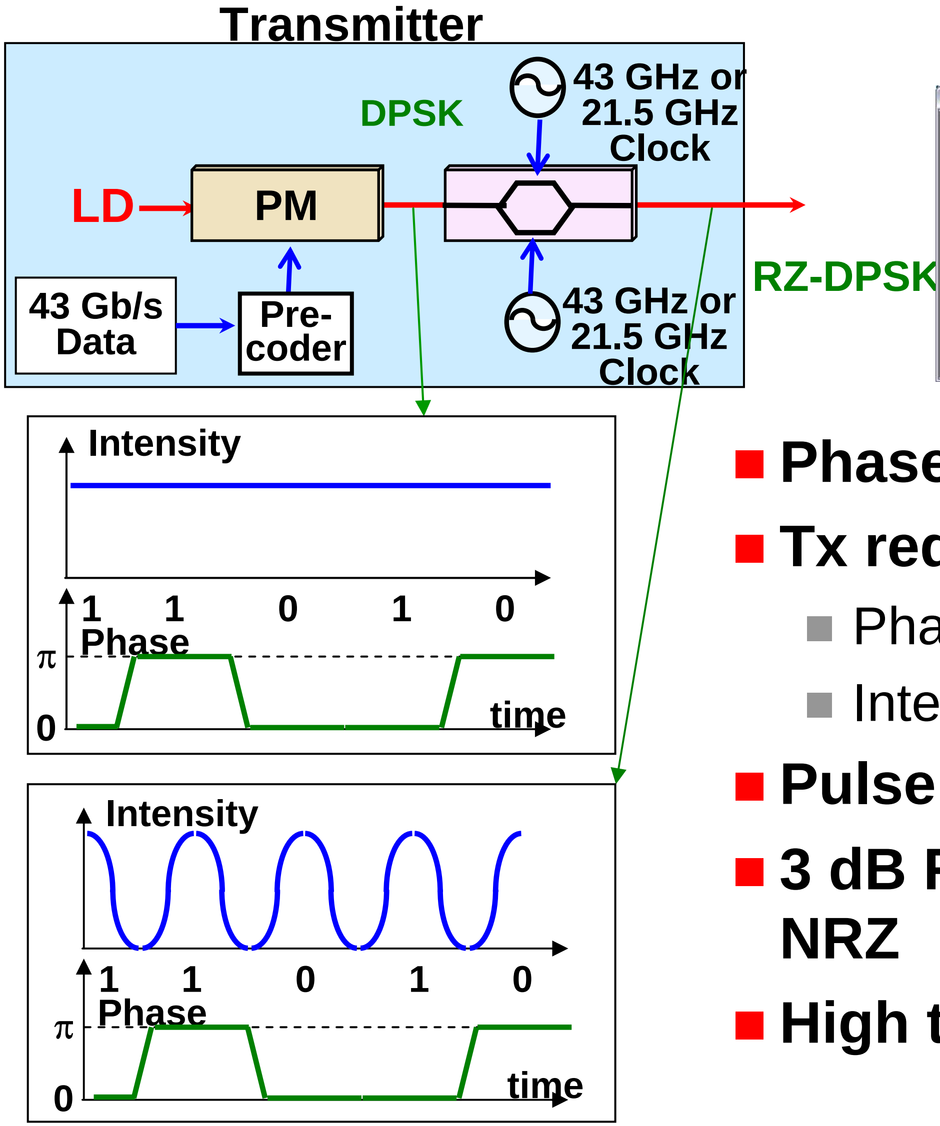
Optical spectrum

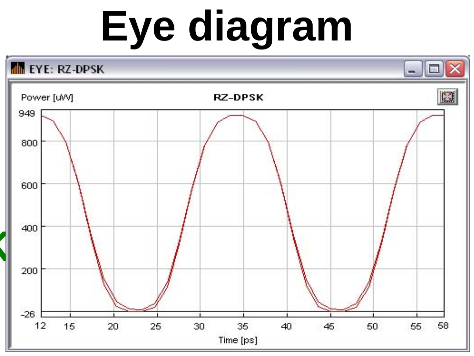


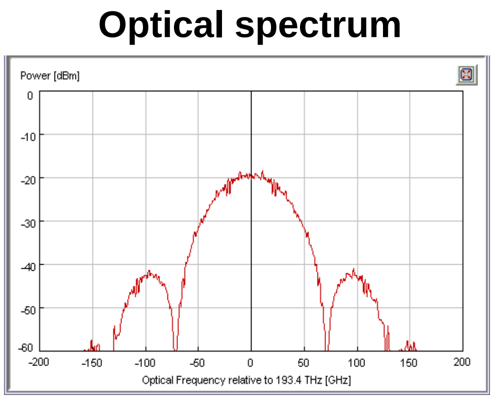
- **Intensity modulation format**
- **Complicated Tx design:**
  - Requires data pre-coder and
  - low pass filter (LPF)
- **Pulse train has NRZ shape with some residual light within "0" symbols**
- **Narrow optical spectrum**
  - Increased spectral efficiency and
  - Large chromatic dispersion tolerance
- **Poor receiver sensitivity: 3 dB worse than NRZ**
- **Poor non-linear tolerance**

K. Yonenaga *et al.*, J. Lightwave Technol., vol. 15, No. 8, pp. 1530-1537, 1997.

Return-to-Zero Differential Phase Shift Keying (RZ-DPSK)







- **Phase modulation format**
- **Tx requires two modulators:**
  - Phase Modulator (PM) and
  - Intensity Modulator (IM)
- **Pulse train has RZ shape**
- **3 dB Rx sensitivity advantage over NRZ**
- **High tolerance to non-linear effects**

Y. Miyano *et al.*, in Proc. OECC'2000, vol. 14D3-3, 2000.

Return-to-Zero Differential Quadrature Phase Shift Keying (RZ-DQPSK)

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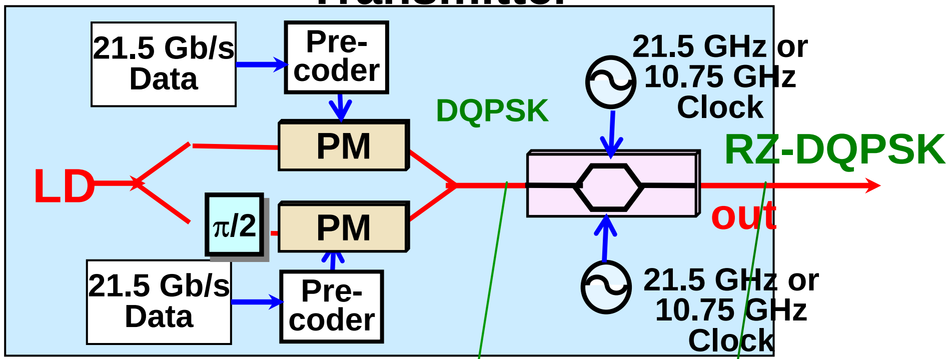
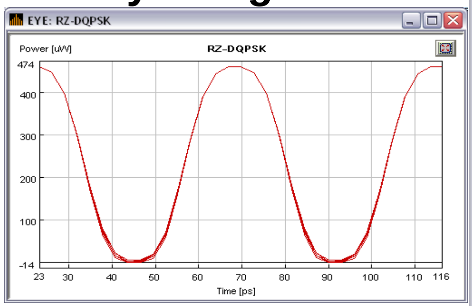
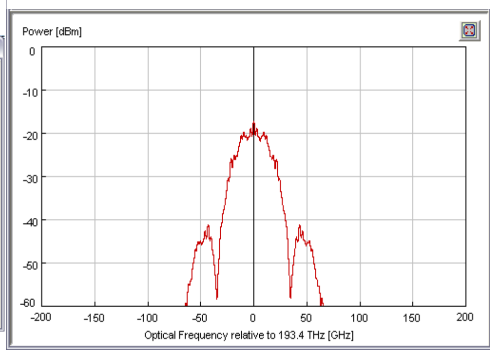
Transmitter

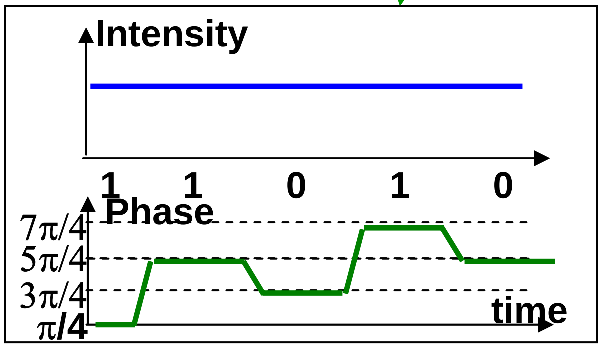


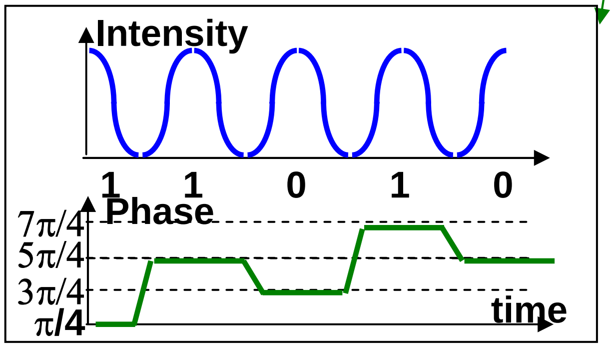
Eye diagram



Optical spectrum



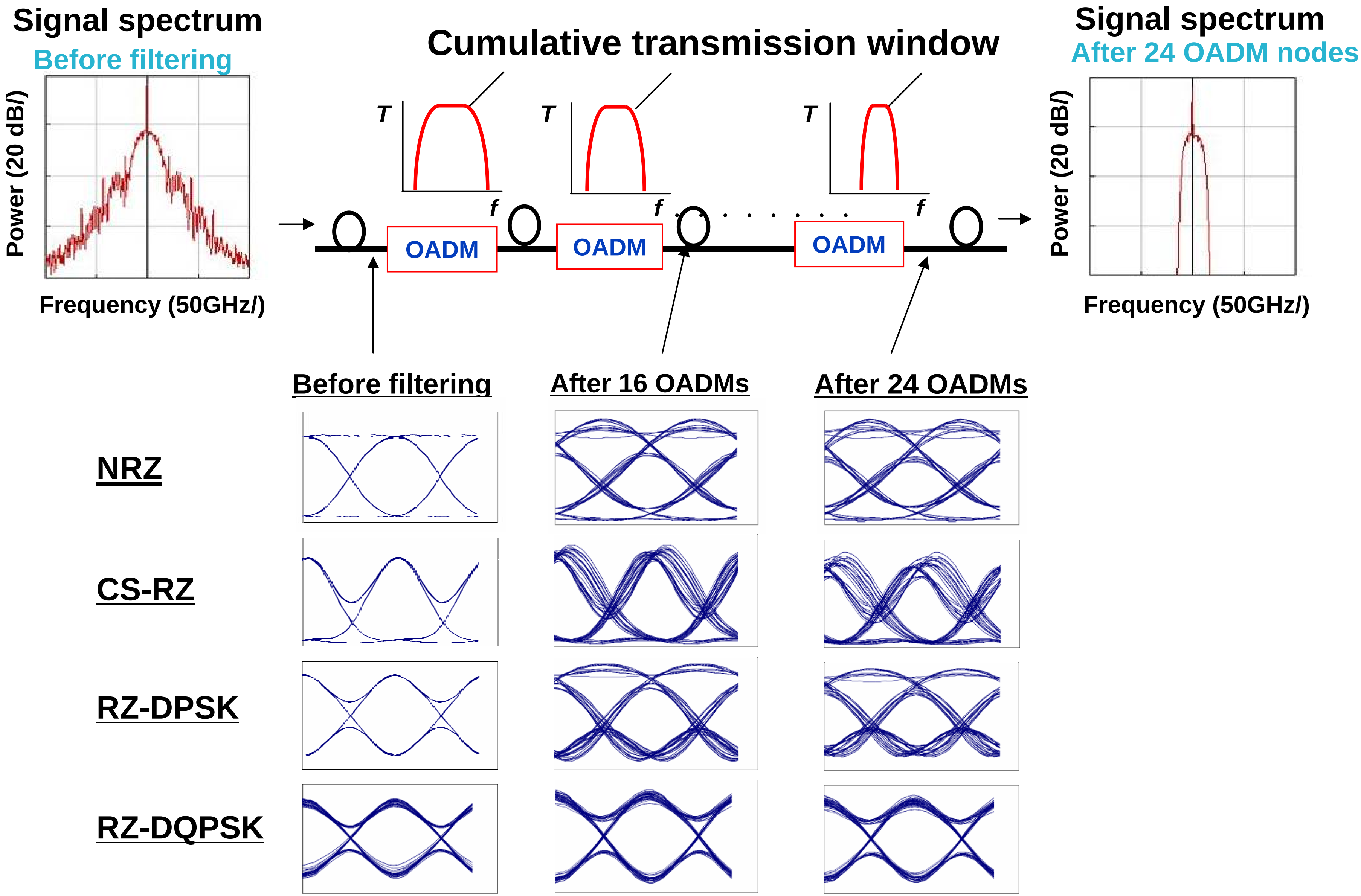




- **Four level phase modulation**
- **Reduced line rate by 50% compared to DPSK:**
  - increased spectral efficiency, PMD and
  - Chromatic dispersion tolerance
- **More complex transmitter design:**
  - two phase modulators and
  - one intensity modulator
- **Pulse train has RZ shape**
- **Optical spectrum is narrow**
- **Has ~3 dB Rx sensitivity advantage over NRZ**

R.A. Griffin *et al.*, in Proc. OFC’2002, WX6, 2002.

Tolerance to OADM Concatenation



Optical Noise Tolerance of 40Gbps Signals

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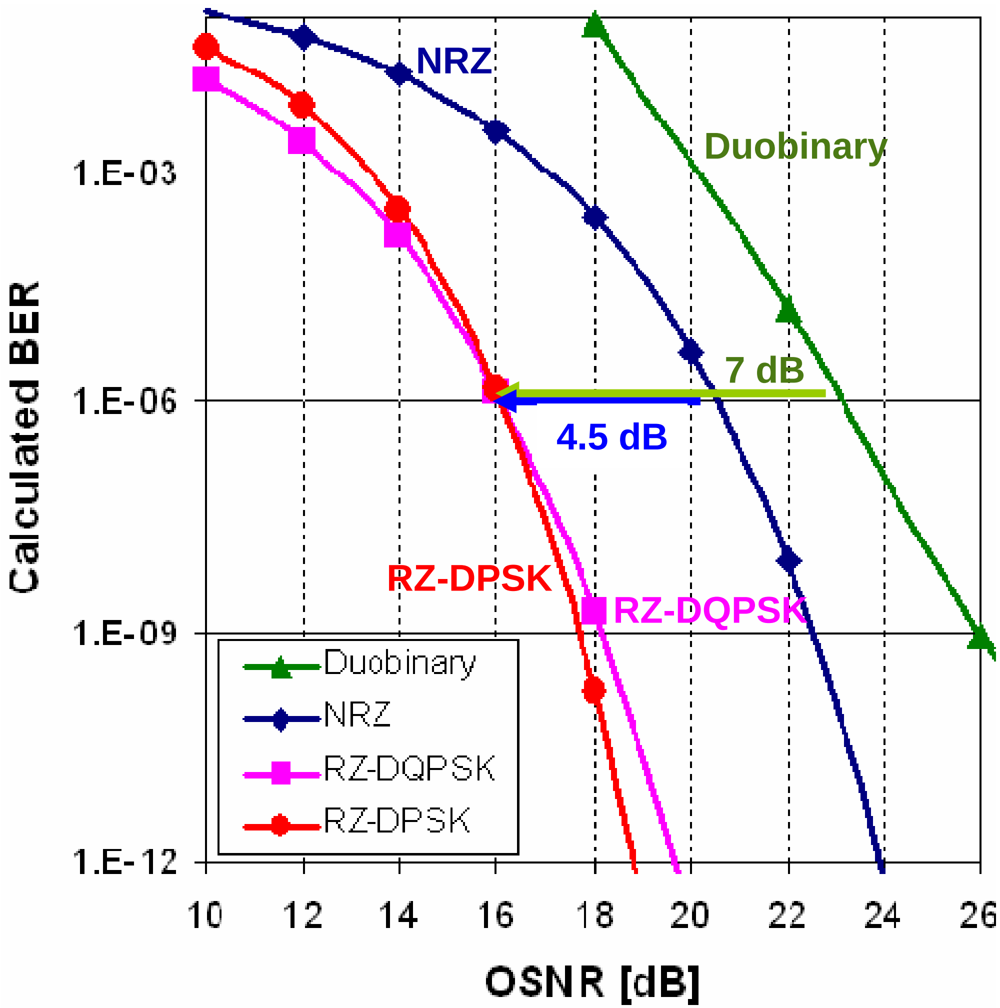
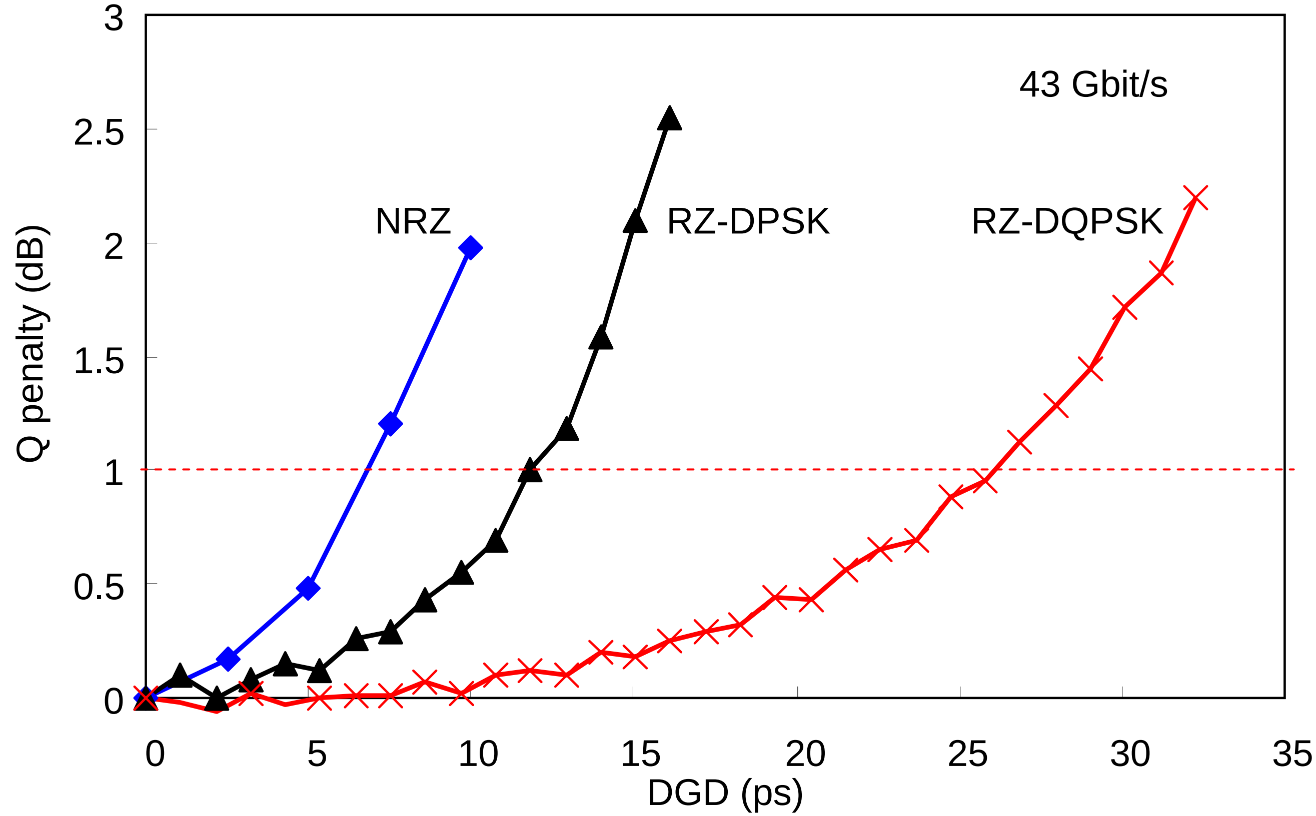
Simulation results



- **Both RZ-DPSK and RZ-DQPSK have high OSNR tolerance**

PMD Tolerance of 40Gbps Signals

Simulation results



- **RZ-DPSK exhibits two times larger PMD tolerance than NRZ due to RZ pulse carving**
- **RZ-DPQSK exhibits even larger tolerance due to halved symbol-rate**

Optical Nonlinearity Tolerance of 40Gbps Signals

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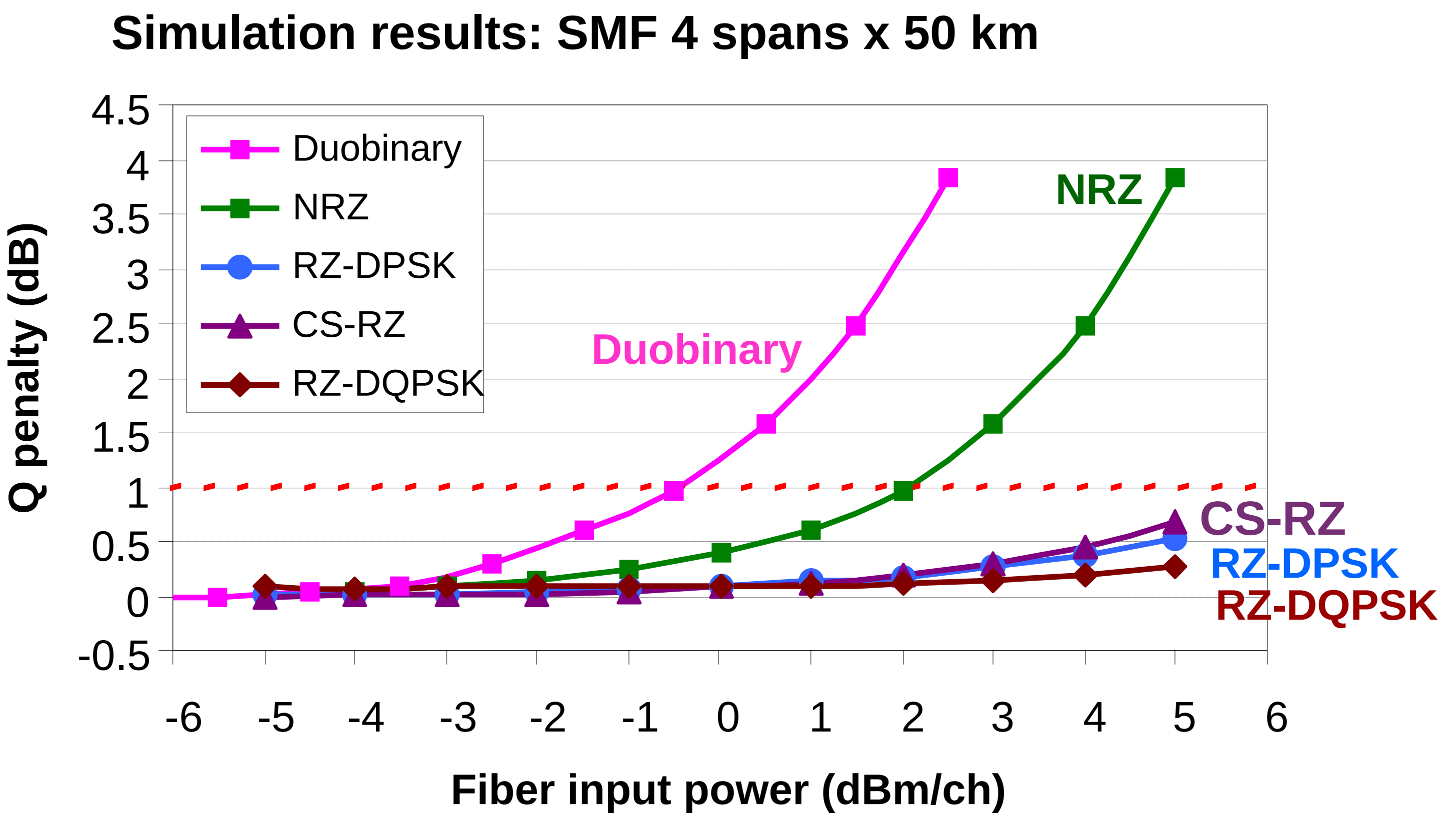
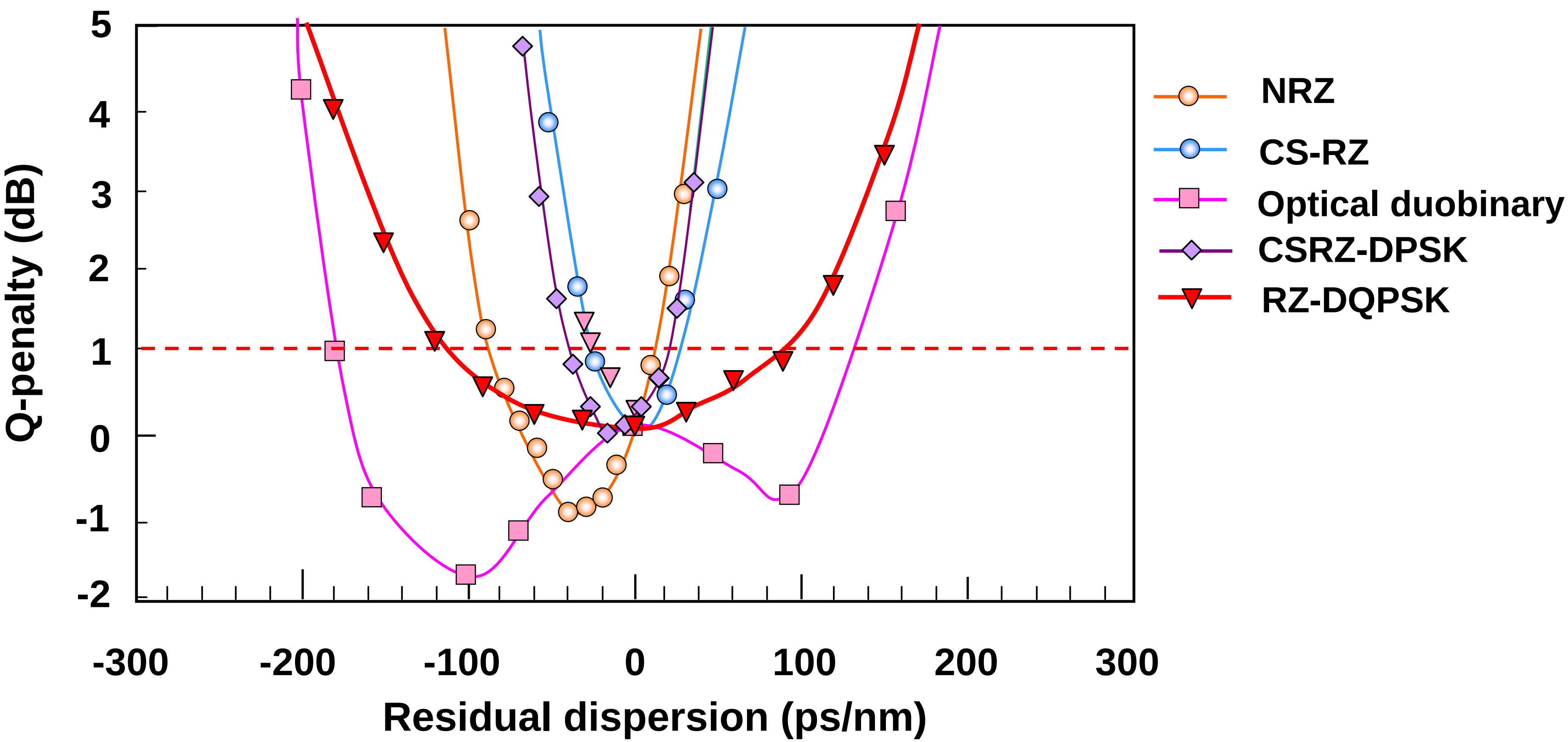


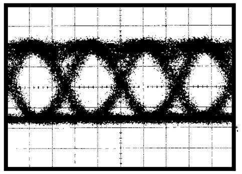
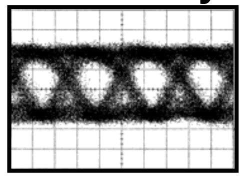
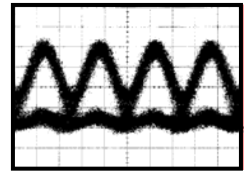
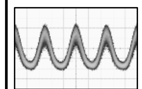
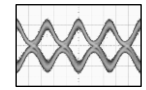
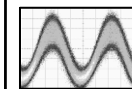
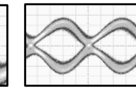
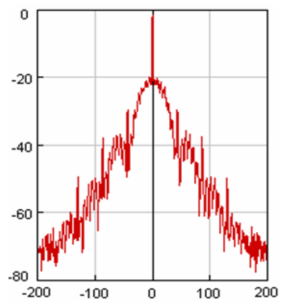
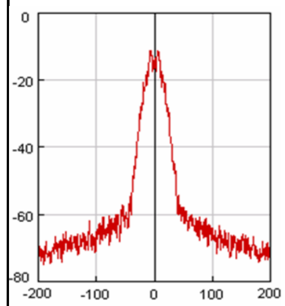
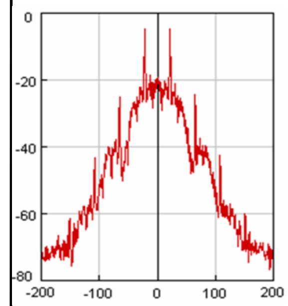
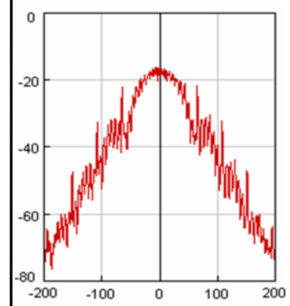
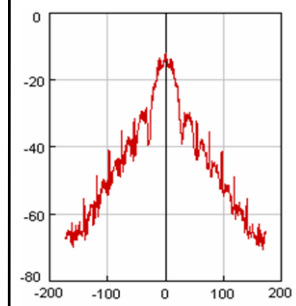
- Advanced modulation formats such as CS-RZ, RZ-DPSK and RZ-DQPSK show high tolerance to non-linear effects

Chromatic Dispersion Tolerance



- RZ-DQPSK and Duobinary show CD high tolerance

40 Gbps Modulation Formats

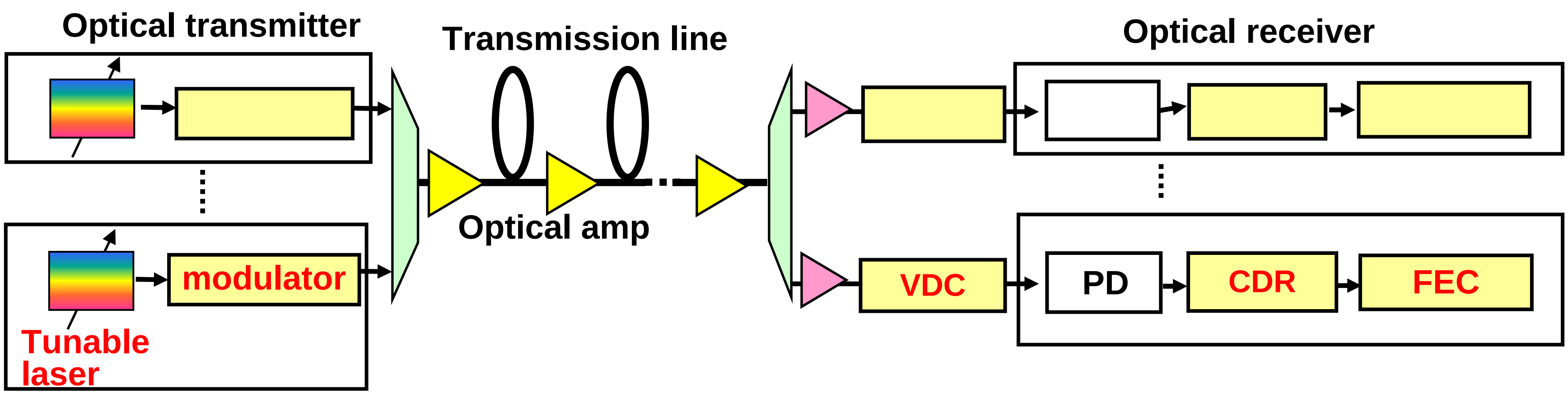
: Advantage : Disadvantage	NRZ	Duobinary	CS-RZ	RZ-DPSK	RZ-DQPSK
				Tx out  MZI out  “1”→ ΔPhase= π “0”→ ΔPhase= 0	Tx out  MZI out  4 values are mapped to Δphase 0, $\pi/2$, π, $3\pi/2$
Optical spectra					
Optical noise tolerance	poor	very poor	medium	very good	good
Chromatic dispersion tolerance	medium	good (in linear regime)	medium	medium	good
PMD tolerance	poor	medium	medium	medium	good
Optical nonlinearity tolerance	medium	poor	good	good	good
OADM filtering tolerance	medium	good	medium	medium	good

- **RZ-DQPSK is attractive in many aspects for high bit-rate transmission**

40Gbps RZ-DQPSK

- **RZ-DQPSK is the best modulation format to enable 40Gbps transmission**
  - Superior filtering tolerance
    - Multiple passes through ROADMs
  - Superior CD tolerance
    - Can support 40Gbps WDM transmission over existing networks
  - Superior PMD tolerance and OSNR performance
    - Longer transmission spans, fewer regeneration sites and increased number of ROADM nodes per network

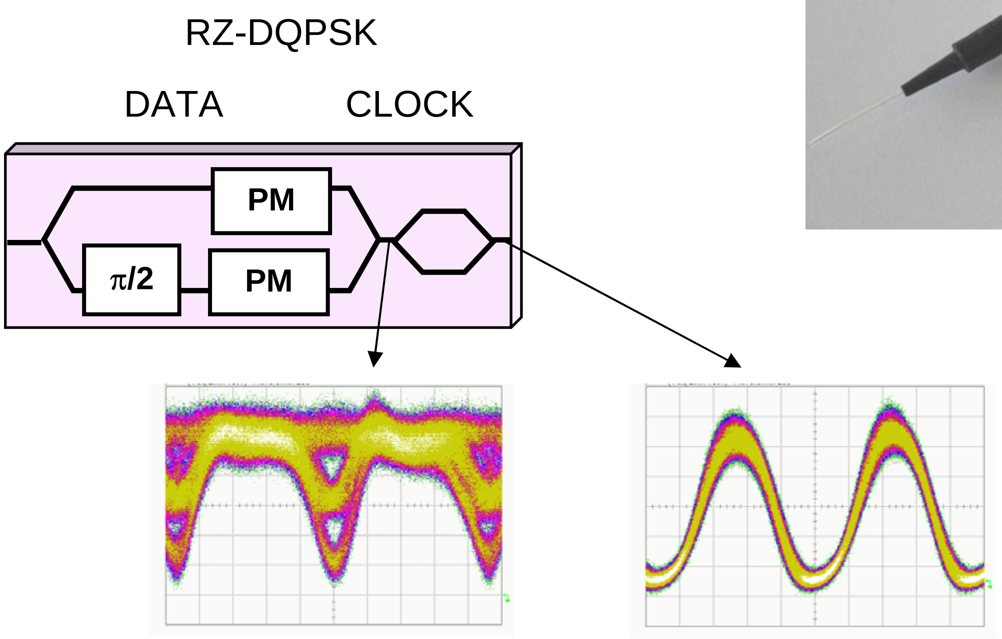
Advanced Technologies to Support 40Gbps Transmission



Device	Characteristic
Tunable laser source	Narrow spectral linewidth & full-band tunability
Modulator	Generates 40Gbps signal
Variable dispersion compensator (VDC)	Operates at any wavelength in entire band with small pass-band effects
High-speed electronic devices	Devices for modulator drivers, preamp, and CDR (clock and data recovery)
High performance error correction technology	Extended transmission distance with minimal bit rate increase

LiNbO3 Modulators for 40Gb/s

- **40 Gb/s low drive voltage DQPSK LN optical modulator**
  - Ultra low 4.0 V drive voltage
  - 25 GHz bandwidth
  - Compact size
  - Integration of phase modulators



40Gb/s RZ-DQPSK Transceiver Module

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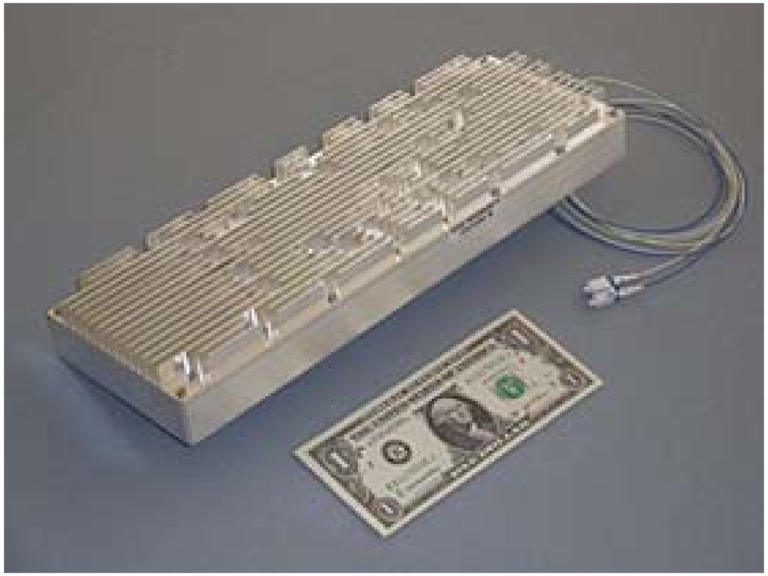
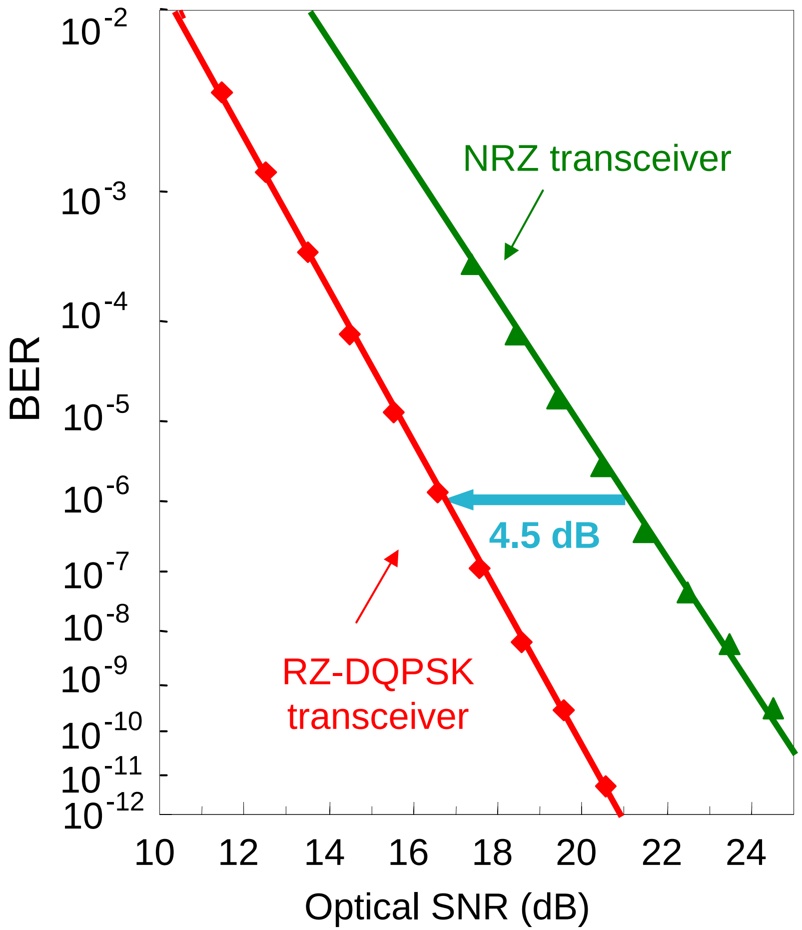
- **Modulation format: RZ-DQPSK**
- **C- and L-band fully tunable**
- **Multi rate: 43 Gb/s, 44.6 Gb/s**
- **SFI-5, 300pin MSA interface**
- **Size: 320mm x 110mm x 40mm**
- **Low power consumption: 35 W**





- **4.5 dB noise tolerance improvement from NRZ format**

  ⇨ **2.8x transmission distance**

40Gb/s RZ-DQPSK Transceiver Performance

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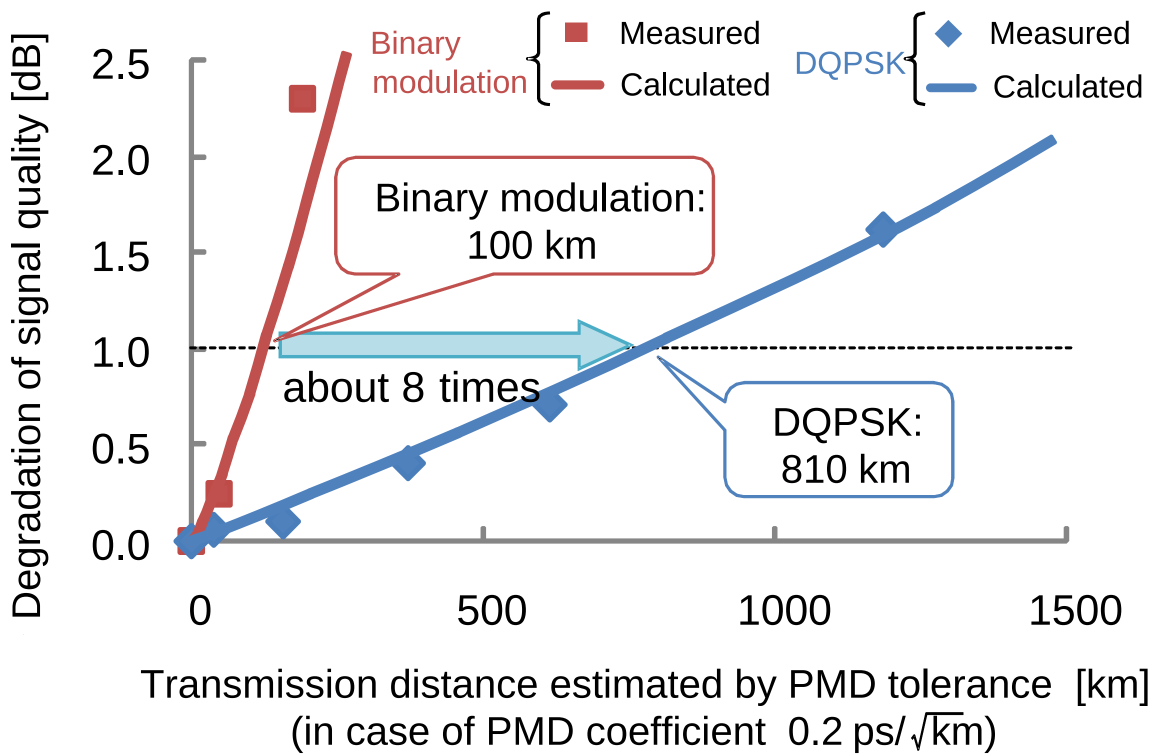
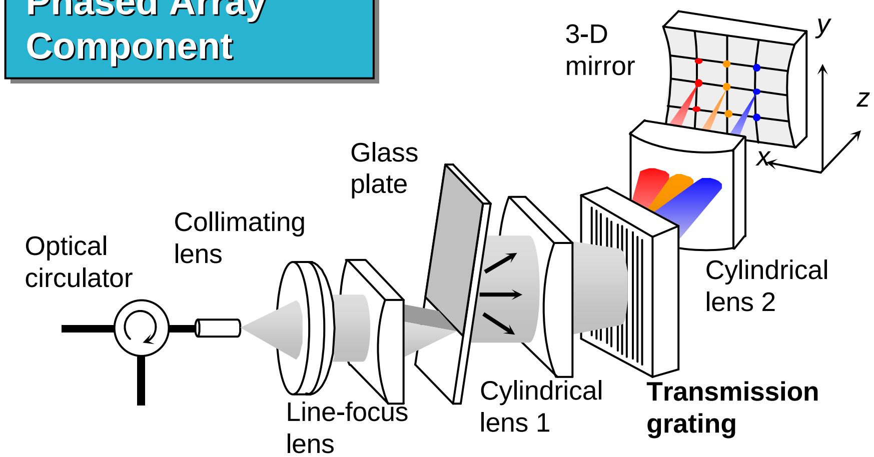


- **Transmission reach limited by PMD was found 8 times better than that of standard binary modulation**
  - Longer spans and fewer regeneration sites

Variable Dispersion Compensation for 40Gbps

Virtually Imaged Phased Array Component



- **Chromatic dispersion in 40Gbps systems**
  - More severe dispersion tolerance
    - ~ 50 ps/nm
    - 1/16 of 10G systems
  - Chromatic dispersion changes with temperature
    - ~60 ps/nm @ 600 km, 50°C change

- **Advantages of available Variable Dispersion Compensation**
  - Replaces "menu" of fixed DCM
  - High tunable dispersion resolution: 1 ps/nm
  - Large variable dispersion range: ± 800 ps/nm
  - No penalty due to fiber nonlinear effect

Deployment Strategies of 40Gbps

- **Green field deployment**
  - Deployment of new 40Gbps DWDM systems

- **Upgrade of already installed 10Gbps DWDM systems***
  - Add 40Gbps line cards to existing 10Gbps DWDM
  - Utilize the same existing transmission infrastructure
    - Same fibers
    - Same dispersion compensating modules (DCM)
    - Same optical amplifiers
    - Same OADM nodes (same OADM filtering properties)

R. Fiorone *et al.,* in Proc. OCOC'2004, Th.2.5.4, 2004.

Upgrade of Existing 10Gbps Networks

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- **Migration to 40Gbps is very simple thanks to currently developed 40Gbps technologies such as:**
  - New spectrally efficient modulation formats (i.e. DQPSK)
  - Variable dispersion compensation

- **Simply add 40Gbps line cards to existing 10Gbps networks**
  - Increase transmission capacity w/o installation of new networks
  - No changes to existing infrastructures – cost savings!
  - No impact on 10Gbps signals

- **10Gbps and 40Gbps signals can co-exist in the same network !**

100+ Gbps Transmission

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- **IEEE 802.3 HSSG is considering multiple approaches**
  - Short haul connections
    - Typically 300-1000 meters for inter-switch links in data centers.
    - Current proposals: 4x CWDM, 5x, 10x parallel
  - Medium-range interface ~ 10 Km, 40Km
    - Current Proposals: 4x, 5x parallel, 1x serial

Question: How to transport 100GE in DWDM networks?

Parallel

- **Transport on multiple wavelengths**
  - Requires synchronization of wavelengths due to differential propagation delay
  - Manage a band of wavelengths
  - Simpler Tx/Rx, but low fiber utilization

Serial

- **Transport on single wavelength**
  - Complex Tx/Rx
  - Higher spectral efficiency
  - Higher total transport capacity over a WDM system
  - Transmission impairments

Transmission Impairments at 100Gbps

- **Transmission impairments are very severe at 100G:**
  - Chromatic dispersion tolerance decreases (1/100-th of 10Gb/s system)
  - PMD tolerance decreases (1/10-th of 10G system)
  - OSNR requirement increases by 10dB
- **Today's networks are mostly designed for 100 GHz ITU grid**
  - Sensitivity to OADM filtering increases
- **Counter-measures**
  - Advanced multi-level modulation formats
    - Low symbol rate
  - Adaptive CD compensation
  - Forward error correction (FEC)
  - Coherent detection
    - PMD and CD tolerance can be further improved

100+ Gbps Serial Transmission

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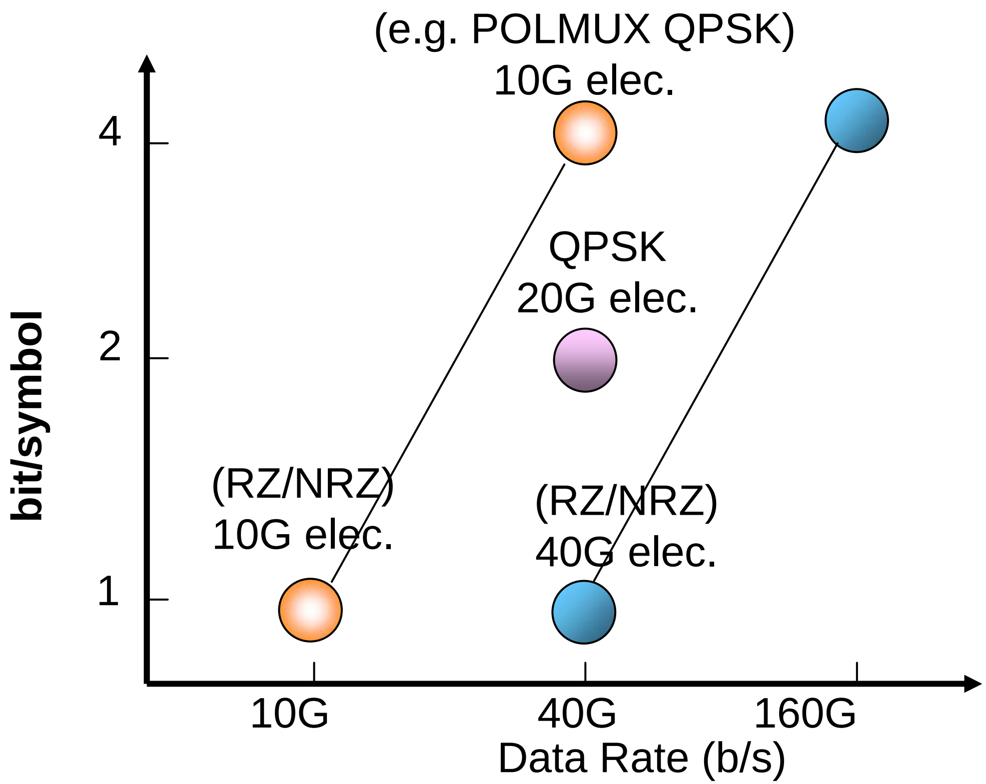
- **How to transport 100GE serially in DWDM networks?**



- (A) Increase data rate OR
- (B) Multi-level modulation (X bits per symbol)

100+ Gbps Serial Transmission (OTDM)

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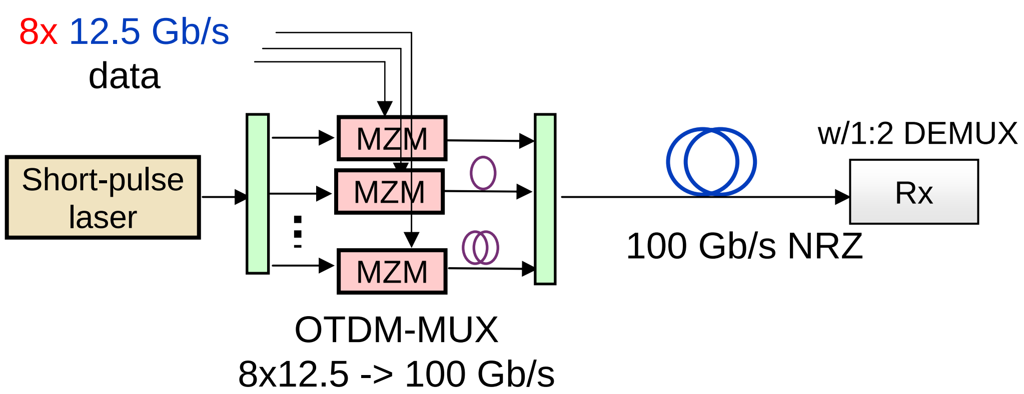
- **Various 100Gbps serial optical transmission experiments have been performed:**

- **(1) Optical time division multiplexing (OTDM) (480km DMF)**

Pros: Low speed electronics

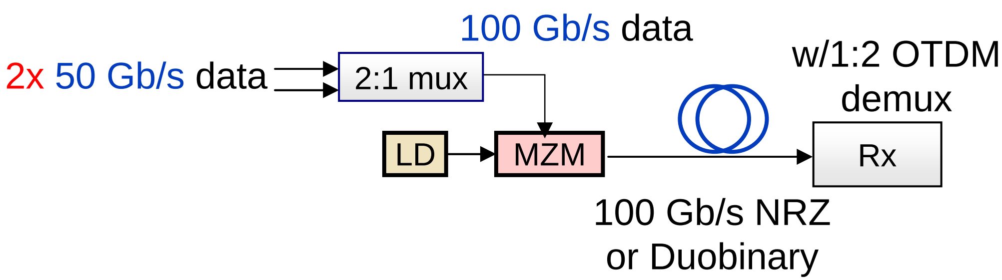
Cons: Requires short-pulse laser source
Transmitter tends to be bulky and expensive
Complex signal processing at the transmitter and receiver
Operation on 100GHz ITU grid is not feasible



R. Derksen *et al.*, in Proc. OFC'2006, PDP37, 2006.

100+ Gbps Serial Transmission (ETDM)

- **(2) Electrical time division multiplexing (ETDM)**
  - 107 Gbps NRZ or Duobinary transmission
  - 100G electronics is not a mature technology
  - Cons: Bandwidth limitation of electro-optical modulator and receiver
    - Operation on 100GHz ITU grid is not feasible



P.J. Winzer *et al.,* in Proc. OCOC'2005, PD paper Th4.1.1, 2005.

C.R. Doerr *et al.,* in Proc. OCOC'2005, PD paper Th4.2.1, 2005.

100+ Gbps Serial Transmission (DQPSK)

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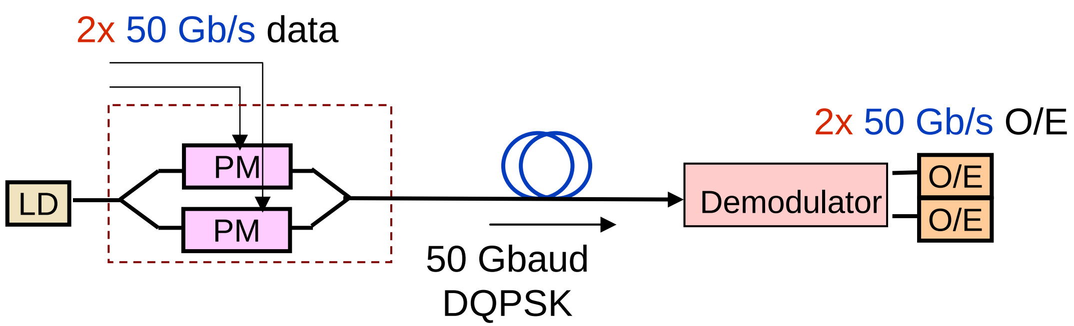
- **(3) DQPSK is a good candidates for 100+Gbps transmission**
  - Pros:
    - Symbol rate 50Gbaud/s
    - Lower speed electronics (50Gbps)
    - Relaxed CD, PMD and OSNR tolerance
    - Operation on 100GHz ITU grid is feasible
  - Cons:
    - Higher complexity of transmitter/receiver



M. Daikoku *et. al,* OFC'2006, PDP36.

100+ Gbps Serial Transmission (POLMUX DQPSK)

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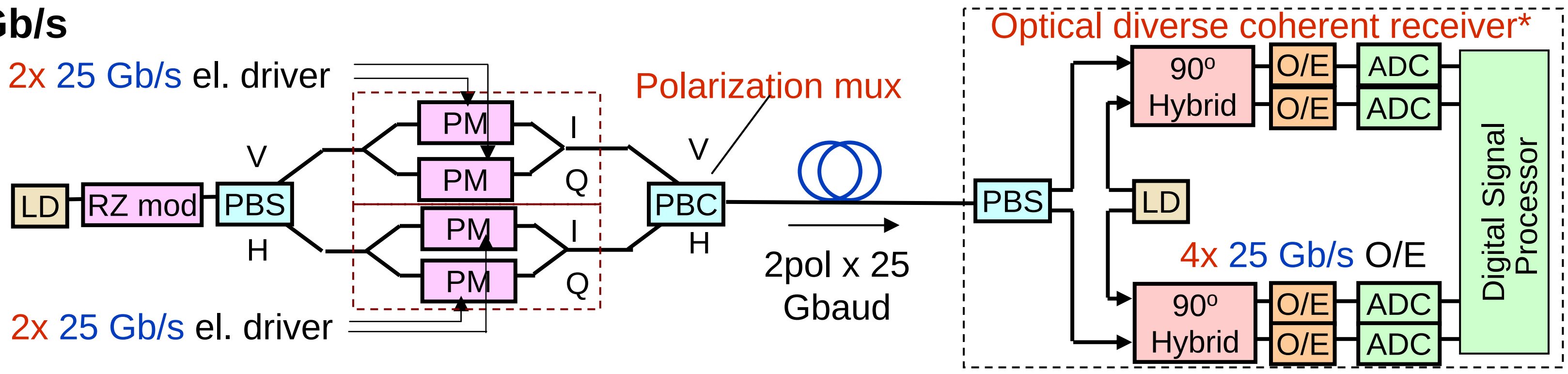
■ (4) POLMUX DQPSK is another candidate

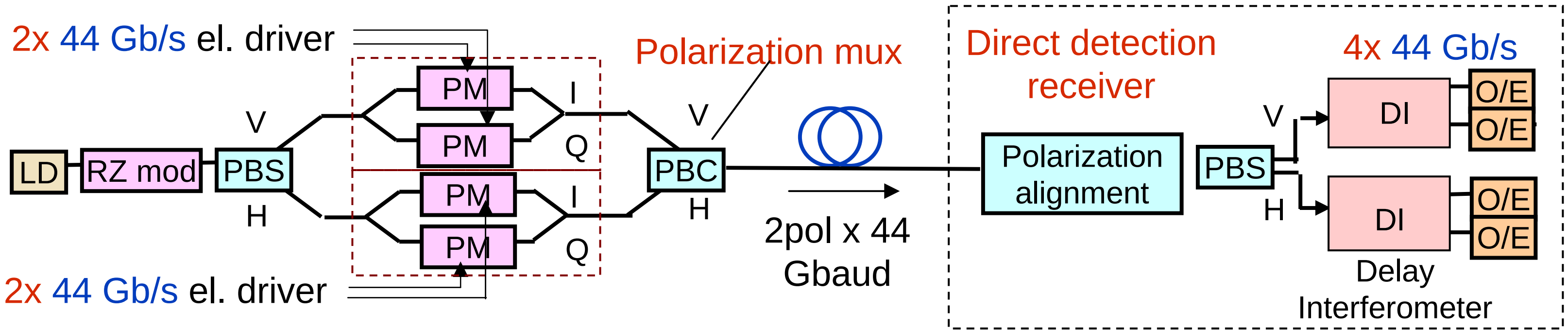
- Low speed electronics (25Gbps)
- Operation on 100GHz ITU grid is feasible
- PMD limited reach and CD tolerance increases due to doubled symbol duration

(A) 100Gb/s



C.R.S. Fludger *et. al,* OFC'2007, PDP22.

(B) 160Gb/s



A.H. Gnauck *et. al,* OCOC'2006, Th4.1.2.

100+ Gbps Champion Experiments

When	Experiment	Distance	Company	Paper
ECOC 2005	107Gb/s Duobinary ETDM Tx, OTDM Rx	-	Alcatel-Lucent	Th.4.1.1
ECOC 2005	107Gb/s NRZ ETDM Tx and OTDM Rx	-	Alcatel-Lucent	Th.4.2.1
OFC 2006	10x107 Gb/s NRZ transmission	400 km	Alcatel-Lucent	PDP32
OFC 2006	100Gb/s DQPSK	50 km	KDDI-NICT-Sumitomo	PDP36
OFC 2006	100Gb/s NRZ ETDM Rx	480 km	HHI-Siemens-Micram	PDP37
ECOC 2006	10x107Gb/s ETDM NRZ OTDM Rx	1000 km	Alcatel-Lucent	Tu.1.5.1.
ECOC 2006	10x107Gb/s RZ-DQPSK transmission	2000 km	Alcatel-Lucent	Th.4.1.3
ECOC 2006	140x111Gb/s PDM-CSRZ-DQPSK	160 km	NTT	Th.4.1.1
OFC 2007	10x107 Gb/s NRZ-DQPSK transmission	1,200 km	Alcatel-Lucent	PDP24
OFC 2007	10x107 Gb/s NRZ transmission	480 km	Alcatel-Lucent	PDP23
OFC 2007	10x111Gb/s PDM-RZ-DQPSK	2,375 km	CoreOptics-Siemens	PDP22
OFC 2007	204x111Gb/s PDM-CSRZ-DQPSK	240 km	NTT	PDP20

100+ Gbps Transmission

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- **100+ Gbps transmission is possible with:**
  - Multi-level modulation (I.e. QPSK)
  - Polarization multiplexing
  - Adaptive CD compensation
  - FEC
  - Coherent detection
    - PMD and CD tolerance can be further improved

- **Advantages of using QPSK:**
  - Low speed electronics
  - Relaxed CD, PMD and OSNR tolerance due to low symbol rate
  - Operation on 100GHz ITU grid is feasible due to narrower optical spectrum
    - Compatibility with existing networks

Summary

- **Discussed 40Gbps enabling technologies**
  - Advanced modulation formats
  - Tunable lasers
  - Variable Chromatic Dispersion Compensator
- **RZ-DQPSK has the best CD, PMD performance and filtering tolerance**
  - Universal solution to 40Gbps Metro/LH applications
- **40Gbps channels can be added to 10Gbps infrastructures without any change of existing networks**
- **Transition from 40G to 100+G is possible with DQPSK**

Thank you!

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THE POSSIBILITIES ARE INFINITE