DQPSK Format for Serial PHY

IEEE 802.3 High-Speed Study Group

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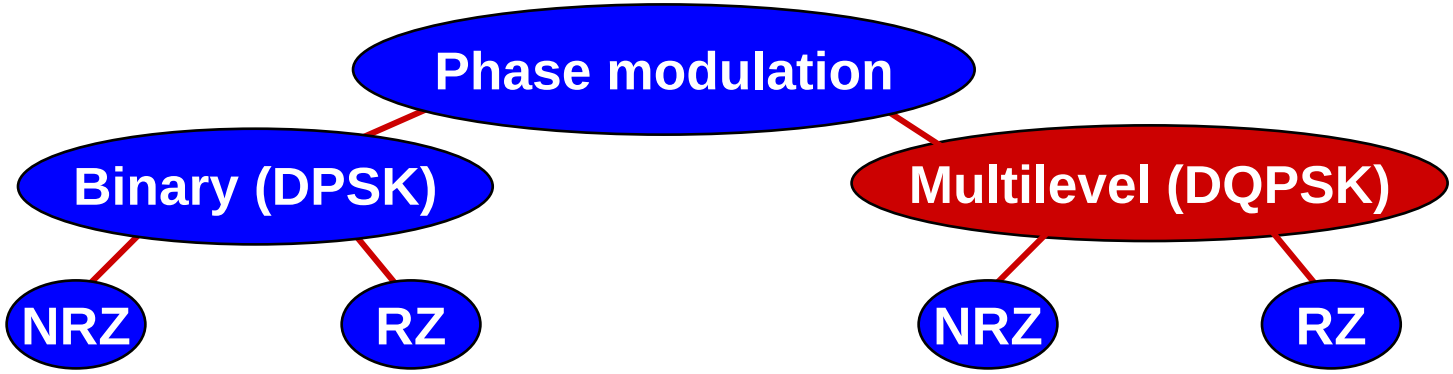
Outline

- What is DQPSK
- Why Use DQPSK for Serial PHY
- Recent Research Demonstrations of 85 Gb/s to 111 Gb/s DQPSK Transmission
- Conclusions

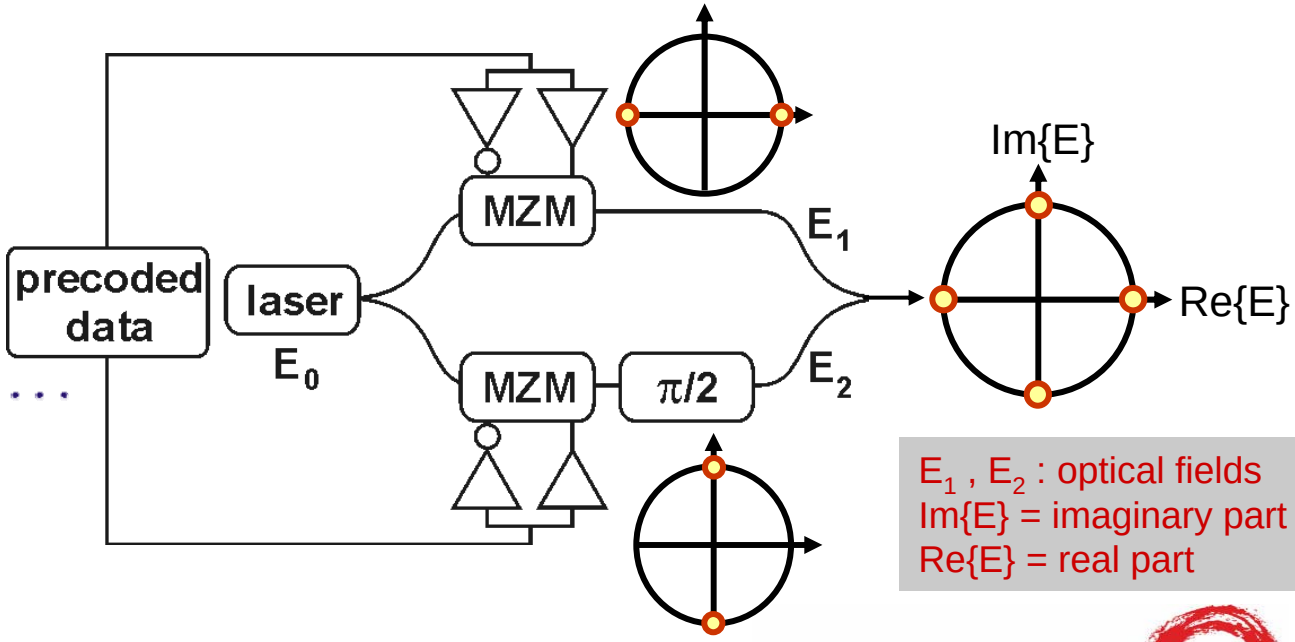
What is DQPSK

- "Phase-Shift Keying" (PSK) captures all modulation formats in which the *phase* of a carrier is modulated
  - 2 phase levels → Binary PSK
  - 4 phase levels → Quadrature PSK (QPSK)
- PSK formats are used widely in wireless networking, e.g. 802.11 WLAN, RFID, 802.15 Bluetooth, etc.
- Direct-detection optical receivers detect *optical power* but not phase
  - Can convert phase *differences* between adjacent bits into power changes by using a delay interferometer
    → *Differential* PSK (DPSK), DQPSK, ...
- QPSK/DQPSK are promising formats for ultra high-speed optical networking because the symbol rate on the transmission line is half the bit rate !
- QPSK and DQPSK differ by the encoding on the TX side and the detection/decoding on the RX side

Quadrature Phase-Shift Keying (QPSK)



Optical Modulation Approach:



$\ldots \underbrace{0\ 0}_{0}\ \underbrace{1\ 0}_{\pi/2}\ \underbrace{0\ 1}_{-\pi/2}\ \underbrace{1\ 1}_{\pi}\ \ldots$

Two bits are replaced by one symbol from a 4-letter alphabet !

E_1 , E_2 : optical fields
Im{E} = imaginary part
Re{E} = real part

1 “baud” = 1 “symbol per second”

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Why DQPSK for Serial PHY

	NRZ	Duobinary	RZ-DPSK	RZ-DQPSK
Bits per Symbol	1	1	1	2
Line Rate (speed of electronics)	100 Gbps (100 Gbaud)	100 Gbps (100 Gbaud)	100 Gbps (100 Gbaud)	100 Gbps **(50 Gbaud)**
SERDES	SiGe / InP	SiGe / InP	SiGe / InP	SiGe
Spectral Efficiency	~0.7 b/s/Hz	~0.8 b/s/Hz	~0.5 b/s/Hz	~1.0 b/s/Hz
Required OSNR (BER 1E-3)	~ 21 dB	~ 24 dB	~18 dB	~ 19 dB
PMD tolerance (1-dB penalty)	~ 3 ps	~ 3 ps	~ 4 ps	~ 8 ps
CD tolerance (2-dB penalty)	± 8 ps/nm	± 25 ps/nm	± 8 ps/nm	± 26 ps/nm

"100G DQPSK = 40G binary modulation with a 25% speed-up"

→ Reuse 40G technology (opto-electronics, SERDES, drivers, etc.)

→ Similar cost structure as 40G but 2.5-times more throughput !

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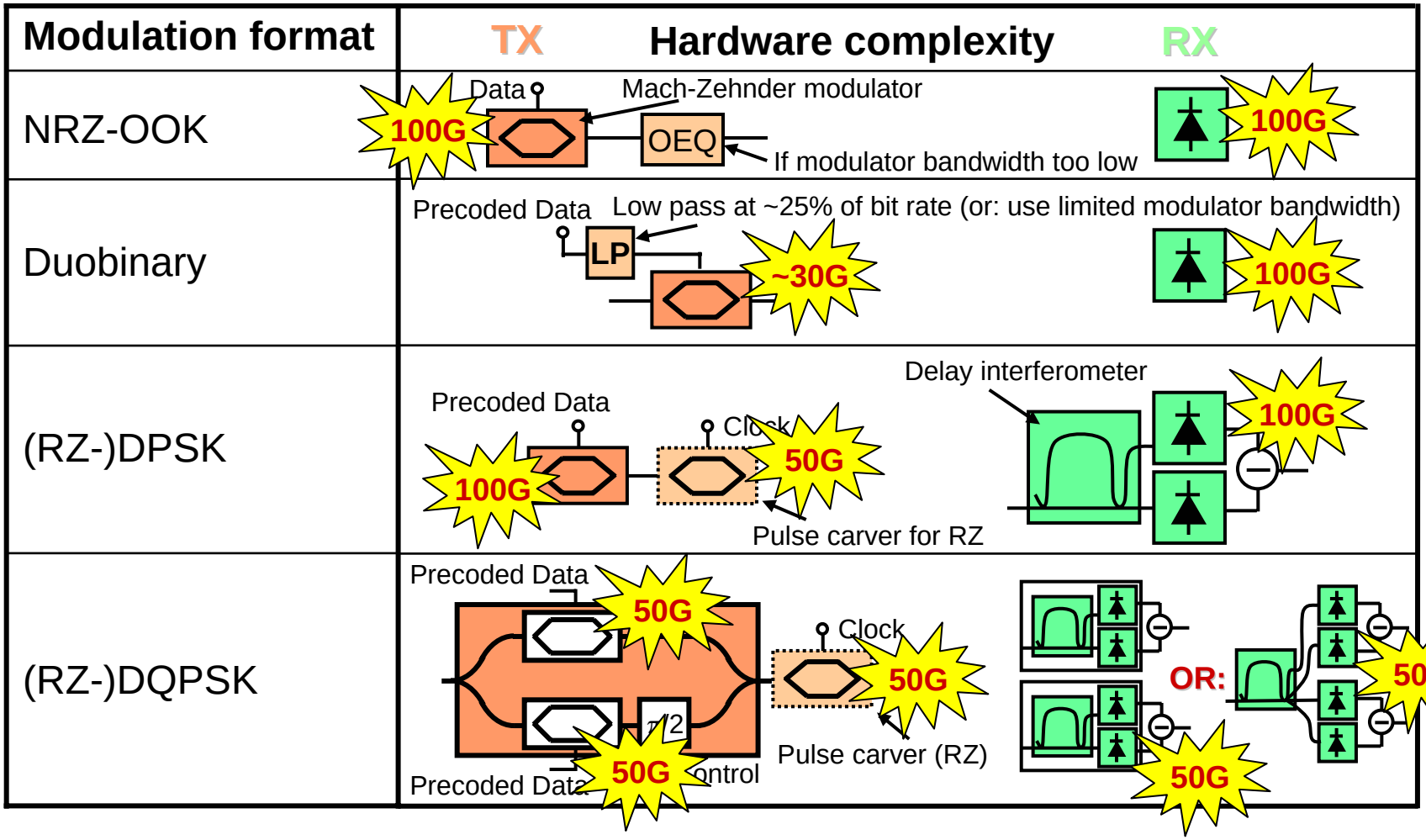
PMD Devices for 100G Serial PHY

100G (serial) DQPSK requires only
50G Electrical & Optical Components !

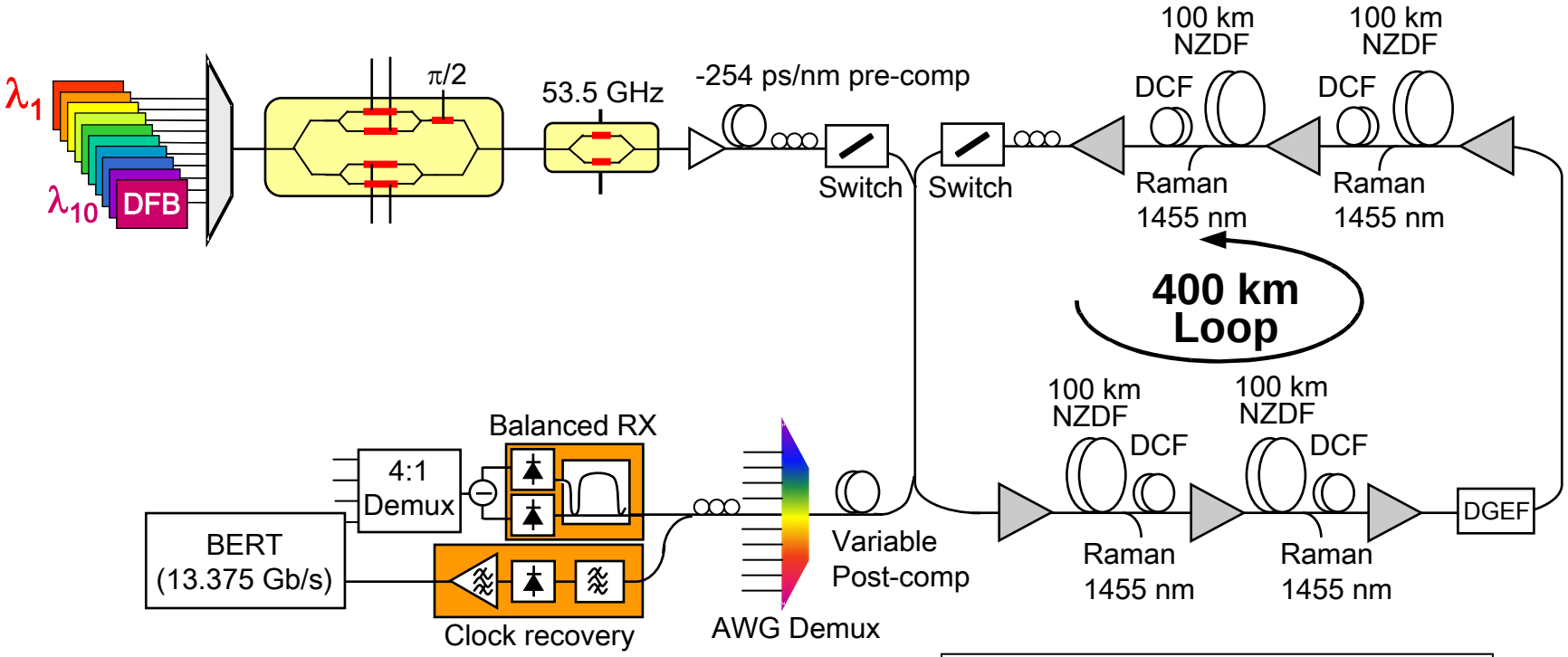


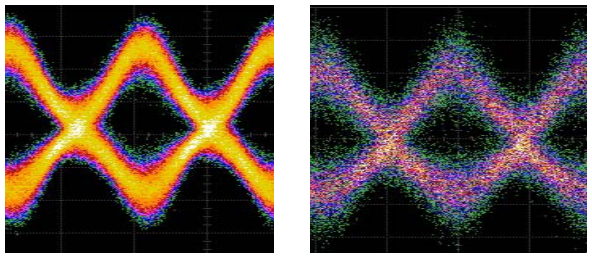
DQPSK Transmission Demonstrations

- Research demonstration of recent optical DQPSK transmission experiments at rates >40 Gbps:
  - 85 Gbps DQPSK transmission of 40 WDM channels with 1.6 b/s/Hz spectral efficiency (PDM) over 1,700 km SSMF, OFC 2006, PD paper PDP34 (COBRA, Siemens)
  - 85 Gbps DQPSK transmission of 64 WDM channels with 0.85 b/s/Hz spectral efficiency over 2,000 km NZDSF, ECOC 2006, paper Mo3.2.3 (Lucent)
  - 85 Gbps DQPSK transmission of 77 WDM channels with 3.2 b/s/Hz spectral efficiency (PDM) over 240 km SSMF, ECOC 2006, PD paper Th4.1.2 (Lucent / Bell Labs)
  - 100 Gbps DQPSK transmission of 1 wavelength channel over 50 km SSMF, OFC 2006, PD paper PDP36 (KDDI)
  - 107 Gbps DQPSK transmission of 10 WDM channels with 0.7 b/s/Hz spectral efficiency over 2,000 km NZDSF, ECOC 2006, PD paper Th4.1.3 (Lucent / Bell Labs)
  - 111 Gbps DQPSK transmission of 140 WDM channels with 2.0 b/s/Hz spectral efficiency (PDM) over 160 km DFF, ECOC 2006, PD paper Th4.1.1 (NTT)

SSMF = Standard Single-Mode Fiber
NZDSF = Non-Zero Dispersion-Shifted Fiber
DFF = Dispersion-Flattened Fiber
PDM = Polarization-Division Multiplexing

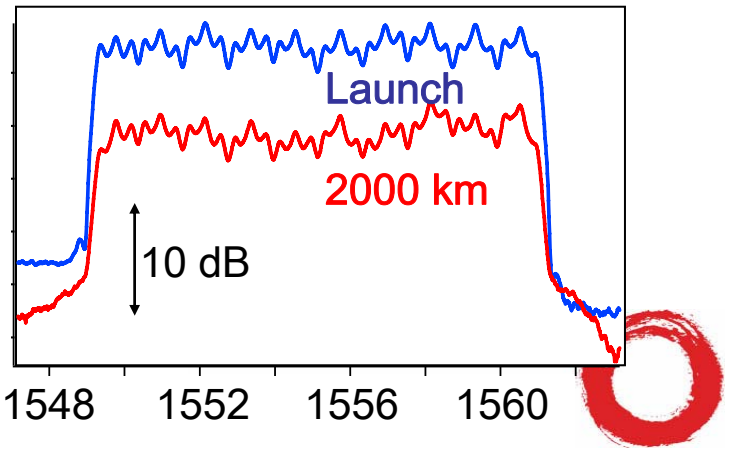
10 x 107-Gb/s WDM 2000-km Transmission





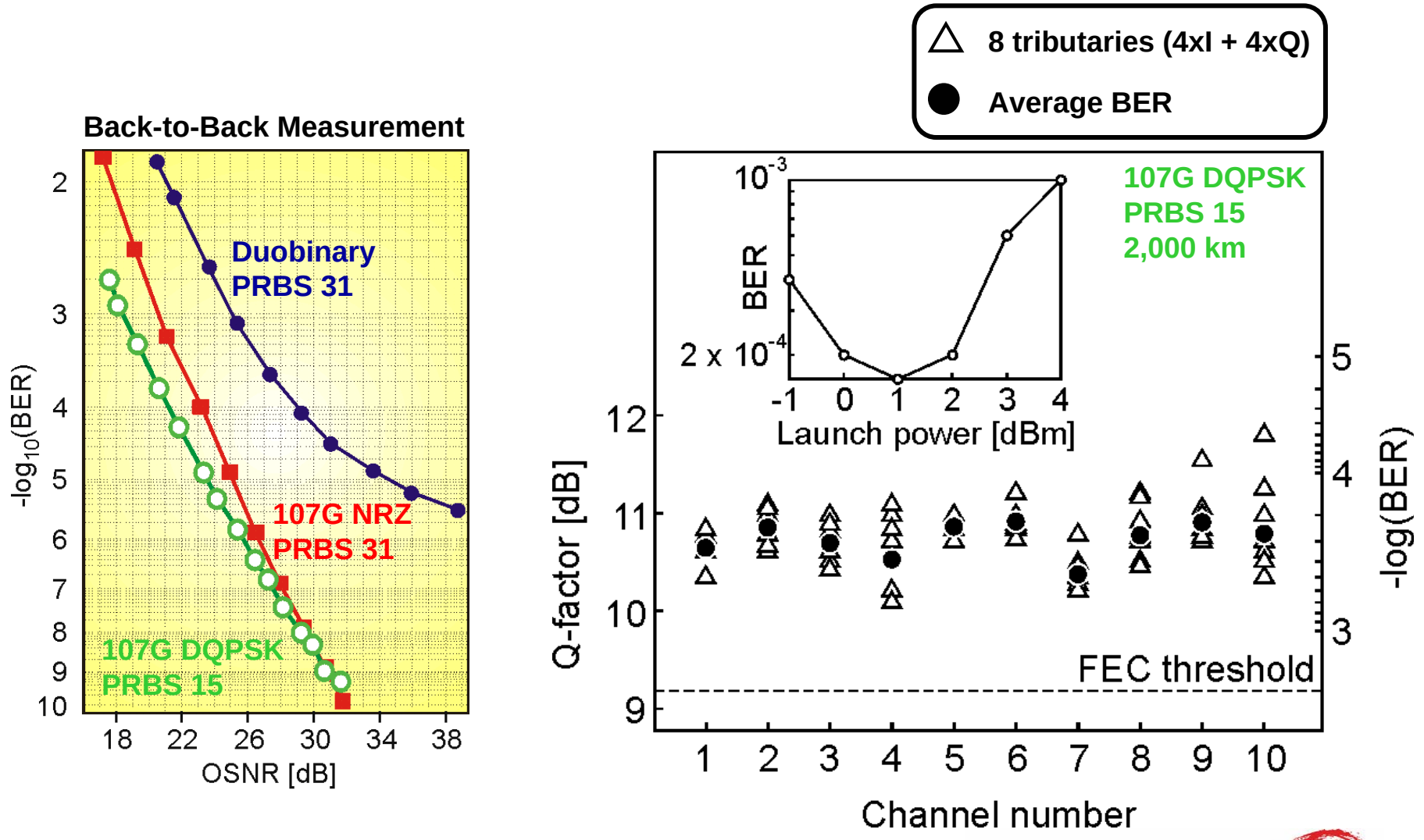
Back-to-back

2000 km



Winzer et al., ECOC 2006, PD paper Th4.1.3

Transmission Results After 2,000 km



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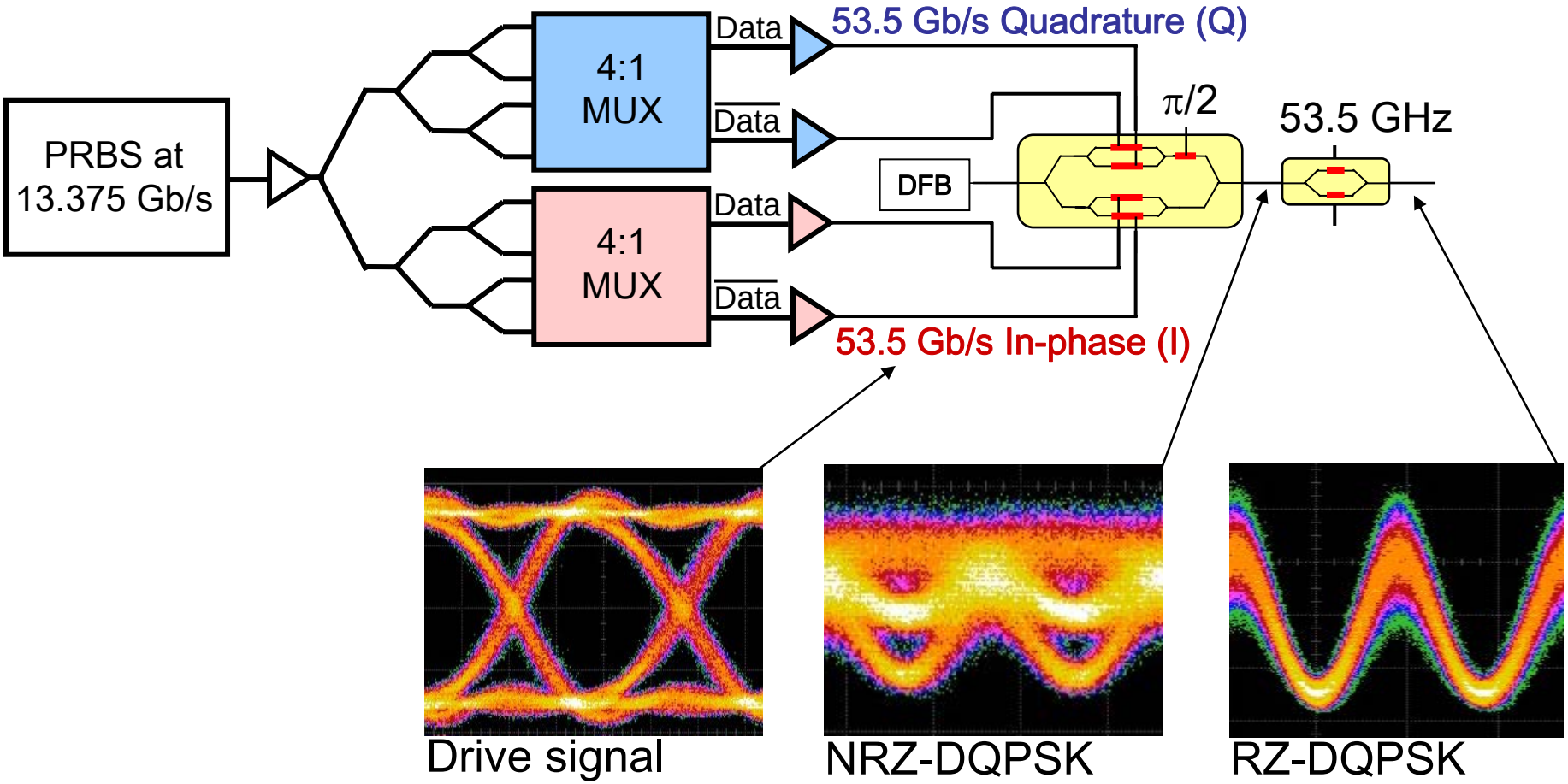
Winzer et al., ECOC 2006, PD paper Th4.1.3

Conclusion

- We propose to consider DQPSK for Serial PHY for Higher-Speed Ethernet because
  - Serial PHY has benefits for WDM networking
  - DQPSK operates at half the symbol rate of binary formats → Reuse 40G Technology with 2.5-times the throughput
  - PMD-limited reach of 100 Gbps DQPSK better than 40 Gbps binary OOK or DPSK
  - High spectral efficiency and long reach (technical feasibility) demonstrated

Backup

107 Gb/s DQPSK Transmitter



Winzer et al., ECOC 2006, PD paper Th4.1.3

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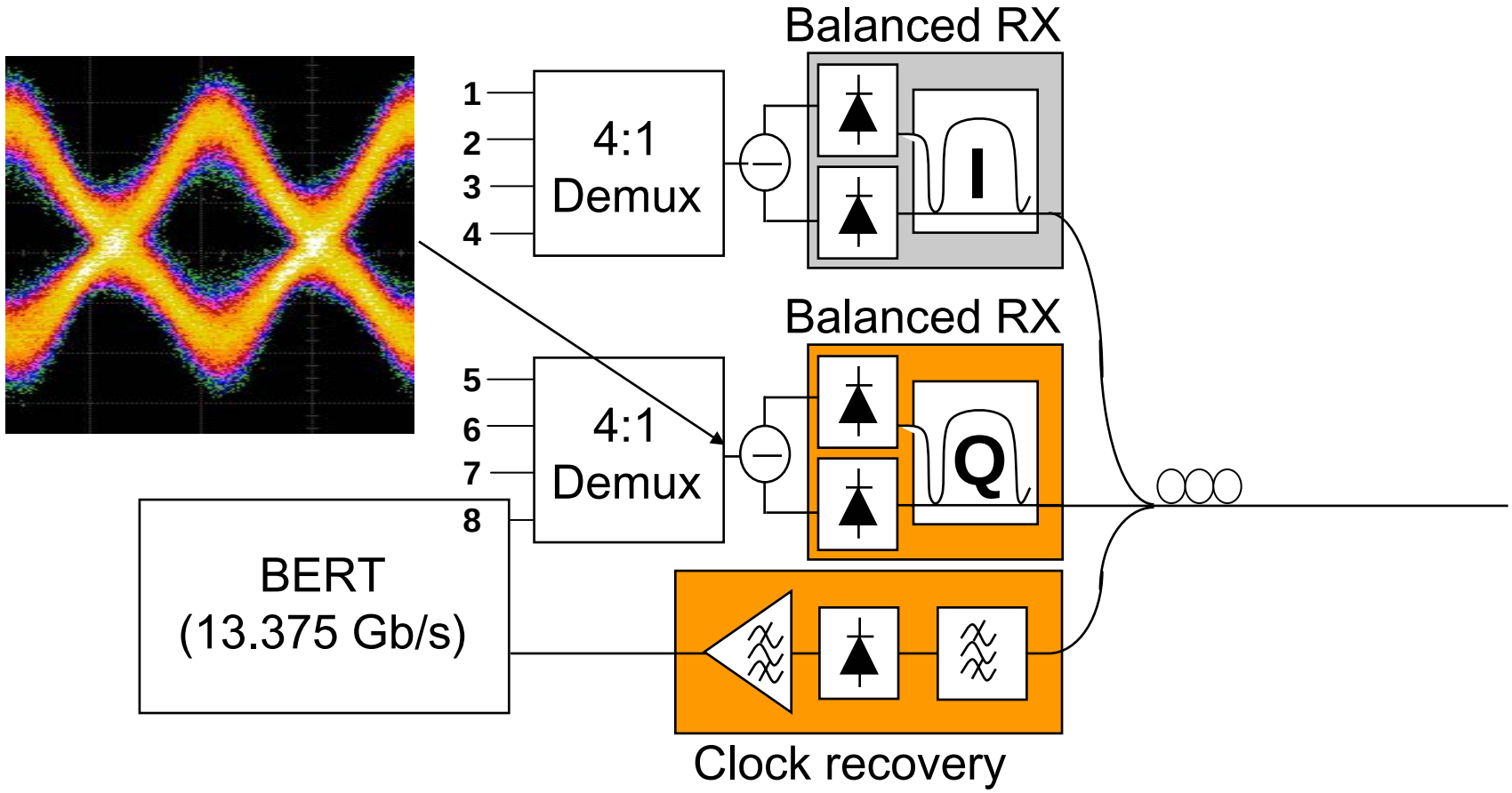
107 Gb/s DQPSK Receiver



High index contrast Si:SiO_2 delay interferometer: 6 mm x 15 mm

Winzer et al., ECOC 2006, PD paper Th4.1.3

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DGD Tolerance vs Modulation Formats

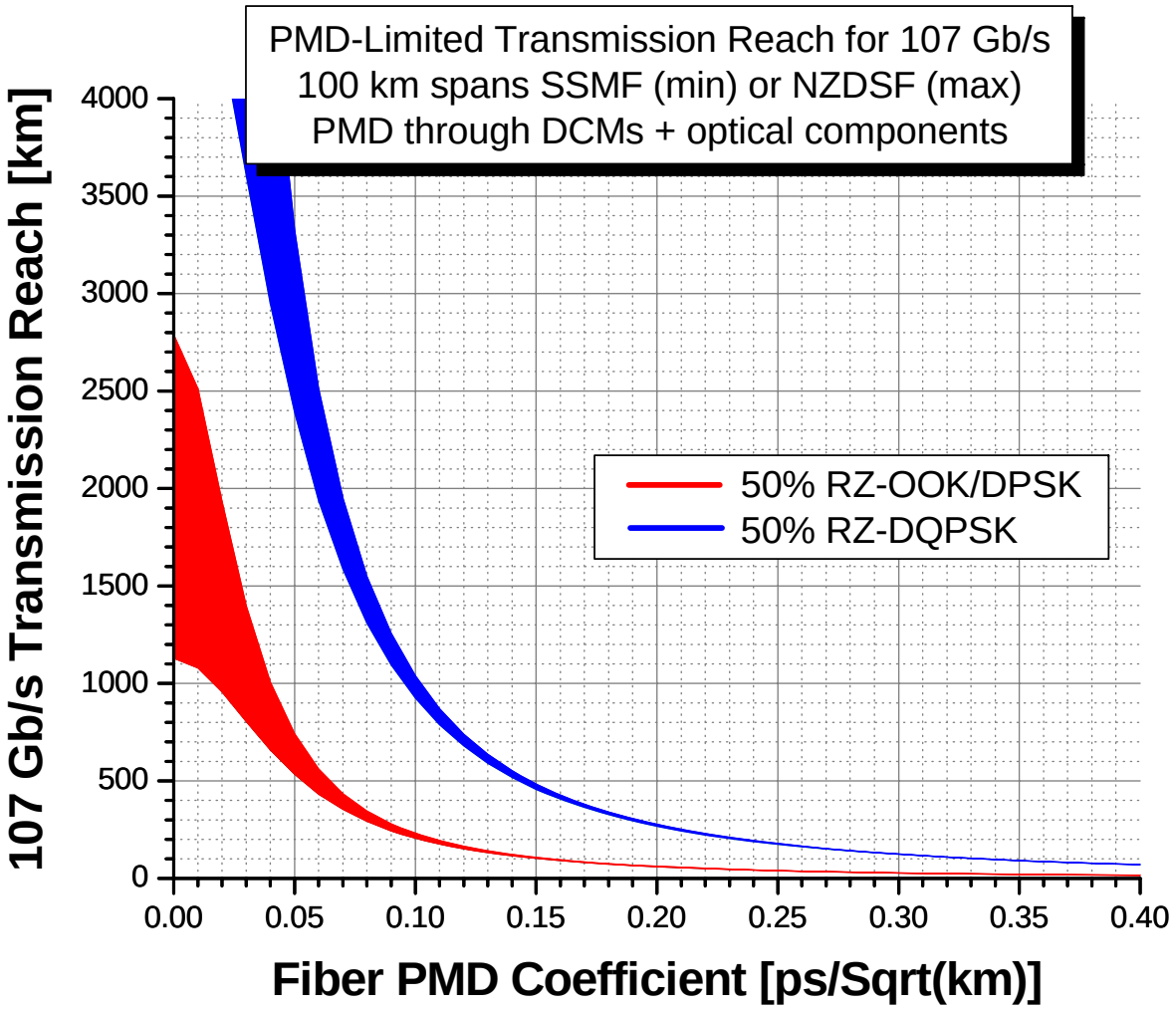
Modulation Format	DGD (1.5 dB Penalty)	<DGD> (1.5 dB Margin, 4E-5 outage)
NRZ-OOK	41%	14%
RZ-OOK	51%	17%
Duobinary	30%	10%
NRZ-DPSK	47%	16%
RZ-DPSK	52%	17%
NRZ-DQPSK	101% **	34% **
RZ-DQPSK	108% **	36% **

- All data are simulated and hold for an OSNR-limited transmission system
- Measured data will depend on exact pulse (eye) shape and receiver characteristics
- All data given for 4E-5 outage probability → DGD = 3×<DGD>
- All data given as percentage of the bit period !
- **: DQPSK has ~twice the PMD tolerance of DPSK because symbol rate on line is reduced by half !

OOK = On-Off Keying
DPSK = Differential Phase-Shift Keying
DQPSK = Differential Quadrature Phase-Shift Keying
NRZ = Non-Return-to-Zero
RZ = Return-to-Zero (here 50% duty cycle)

PMD-Limited Reach for 1x100 Gbps PHY

For 4E-5 Outage Probability !



Less Dispersion-Compensating Fibers (DCFs) needed if spans with Non-Zero Dispersion-Shifter Fibers (NZDSF) are used instead of Standard Single-Mode Fiber (SSMF) → lower PMD → higher PMD-limited reach with NZDSF

(if DCF-based DCMs are used, otherwise equal reach !)

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