Combatting and equalizing the effects of PMD in 40Gb/s systems and beyond

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Includes updated viewgraphs and reference list

Overview

- Introduction
- Electrical PMD compensation
- PMD detection
  - 1st-order PMD detection
  - Higher-order PMD detection
  - Polarization scrambling
- Optical PMD compensation
- Polarization division multiplex
- Conclusions

Small-signal intensity modulation transfer function of a linear lossless optical medium

Input field for unchirped, small-signal ($|a| \ll 1$) intensity modulation:

$$\mathbf{E}_{in} = \left(e^{j\omega_0 t} + (a/4) e^{j(\omega_0+\omega)t} + (a/4) e^{j(\omega_0-\omega)t} \right) \mathbf{e}_{in}$$

Output field after transfer through medium with transfer function/matrix $\mathbf{J}$:

$$\mathbf{E}_{out} = \left(e^{j\omega_0 t} \mathbf{J}(\omega_0) + (a/4) e^{j(\omega_0+\omega)t} \mathbf{J}(\omega_0+\omega) + (a/4) e^{j(\omega_0-\omega)t} \mathbf{J}(\omega_0-\omega) \right) \mathbf{e}_{in}$$

Definition of intensity (normalized optical power, photocurrent): $I = |\mathbf{E}|^2$

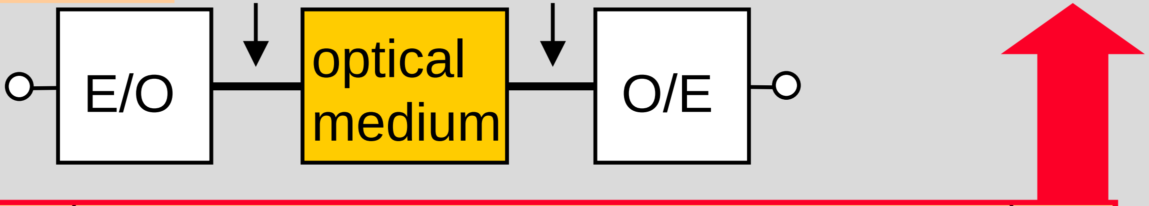
Optical distortions can only partly be recovered in the electrical domain!

Intensity transfer through medium:

$$I_{in} = 1 + a\cos\omega t = 1 + a\,\mathrm{Re}\left(e^{j\omega t}\right)$$

$\mathbf{E}_{in}$ $\mathbf{E}_{out}$

$$I_{out} = 1 + a\,\mathrm{Re}\left(H_m(\omega) e^{j\omega t}\right)$$



$$H_m(\omega) = (1/2)\mathbf{e}_{in}^{+} \left(\mathbf{J}^{+}(\omega_0)\mathbf{J}(\omega_0+\omega) + \mathbf{J}^{+}(\omega_0-\omega)\mathbf{J}(\omega_0) \right) \mathbf{e}_{in}$$

What is polarization mode dispersion (PMD)?

Unitary Jones matrix: $\mathbf{J}(\omega_0+\omega)=\begin{bmatrix} u_1 & u_2 \\ -u_2^* & u_1^* \end{bmatrix}$ $\quad |u_1|^2+|u_2|^2=1$

PMD vector $\mathbf{\Omega} := \mathbf{\Omega}_n \tau = 2\begin{bmatrix} A \\ \operatorname{Re} B \\ \operatorname{Im} B \end{bmatrix}$

$$A=-j\left(u_1^* u_1' + u_2 u_2^{*\prime}\right)$$

$$B= j\left(u_2 u_1^{*\prime} - u_1^* u_2'\right)$$

Principal state-of-polarization (PSP)

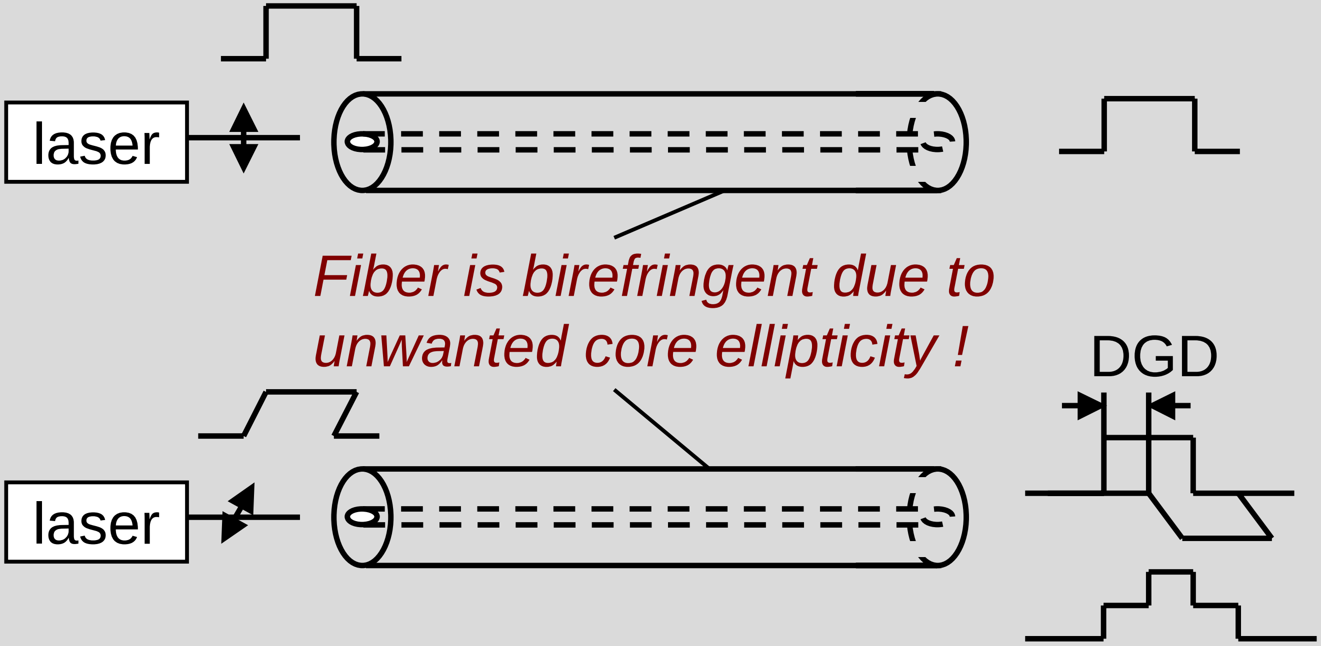
Differential group delay (DGD)

Modulation transfer function for $\omega \rightarrow 0$:

$$H_m(\omega) \sim \cos \omega\tau/2 + j\mathbf{\Omega}_n^T \mathbf{S}_{in} \sin \omega\tau/2 \qquad \mathbf{S}_{in} = \pm\mathbf{\Omega}_n \;\Rightarrow\; H_m(\omega) \sim e^{\pm j\omega\tau/2}$$

- PMD effect scales with bit rate.
- 1st derivative of output polarization with respect to optical frequency vanishes for PSPs (Poole/Wagner, 1986)!

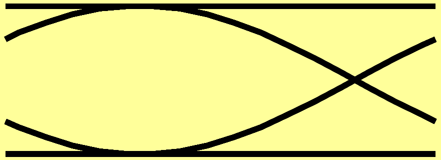
Pure 1st-order PMD



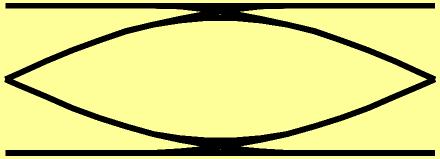
Fiber is birefringent due to unwanted core ellipticity !

Eye closure $\propto \tau^2 \Rightarrow$ difficult to detect for small τ

Eye diagrams (DGD = 3T/8):



Fast PSP



Both PSPs excited with equal powers = worst case

Small-signal modulation transfer function of two DGD sections

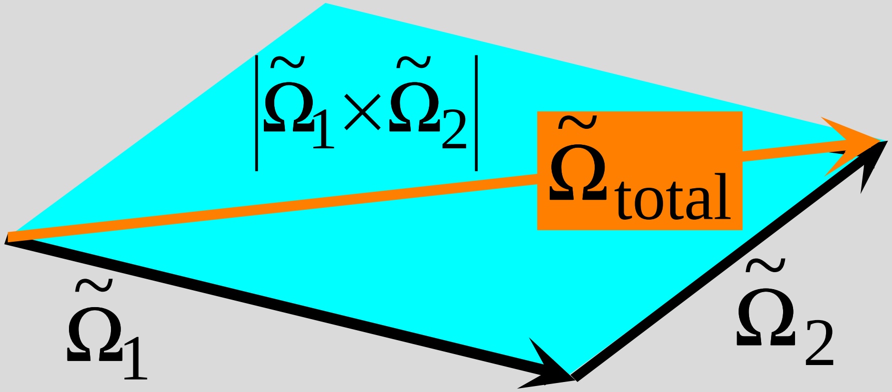
- $$H_m(\omega) = \cos(\omega\tau_1/2)\cos(\omega\tau_2/2) - \sin(\omega\tau_1/2)\sin(\omega\tau_2/2)\tilde{\mathbf{\Omega}}_{1n}^T\tilde{\mathbf{\Omega}}_{2n} + j\left(\sin(\omega\tau_1/2)\cos(\omega\tau_2/2)\tilde{\mathbf{\Omega}}_{1n}^T + \sin(\omega\tau_2/2)\cos(\omega\tau_1/2)\tilde{\mathbf{\Omega}}_{2n}^T\right)\mathbf{S}_{in}$$

  ($\tau_{1,2}$ = section DGDs; $\tilde{\mathbf{\Omega}} = \tilde{\mathbf{\Omega}}_n\tau$ = input-referred PMD vector)

- Approximations for $|\omega\tau_i| << 1$ yield geometrical interpretation using PMD vector direction/length and PMD profile area:

$$\mathbf{S}_{in} = \pm\tilde{\mathbf{\Omega}}_{n,\text{total}}^T \quad \Rightarrow$$

$$|H_m(\omega)|^2 \approx 1 - \left((\omega/2)^2\left|\tilde{\mathbf{\Omega}}_1 \times \tilde{\mathbf{\Omega}}_2\right|\right)^2$$



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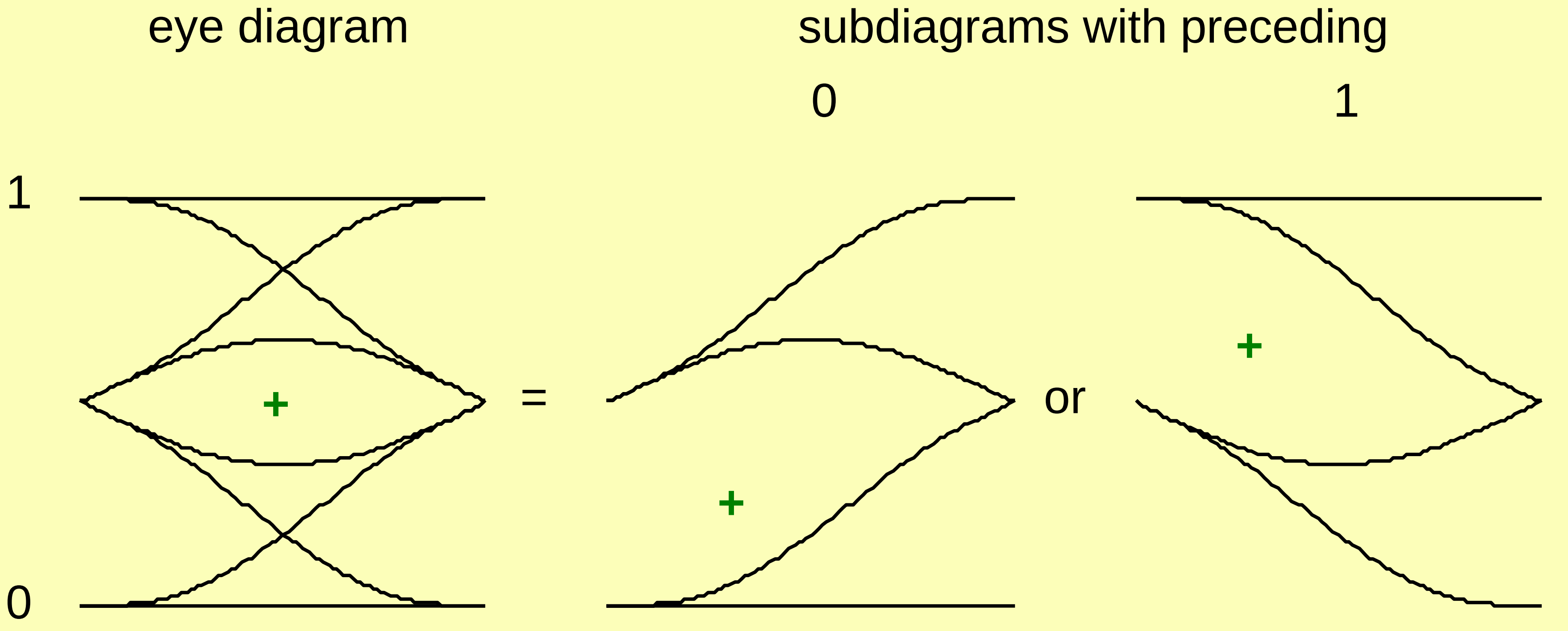
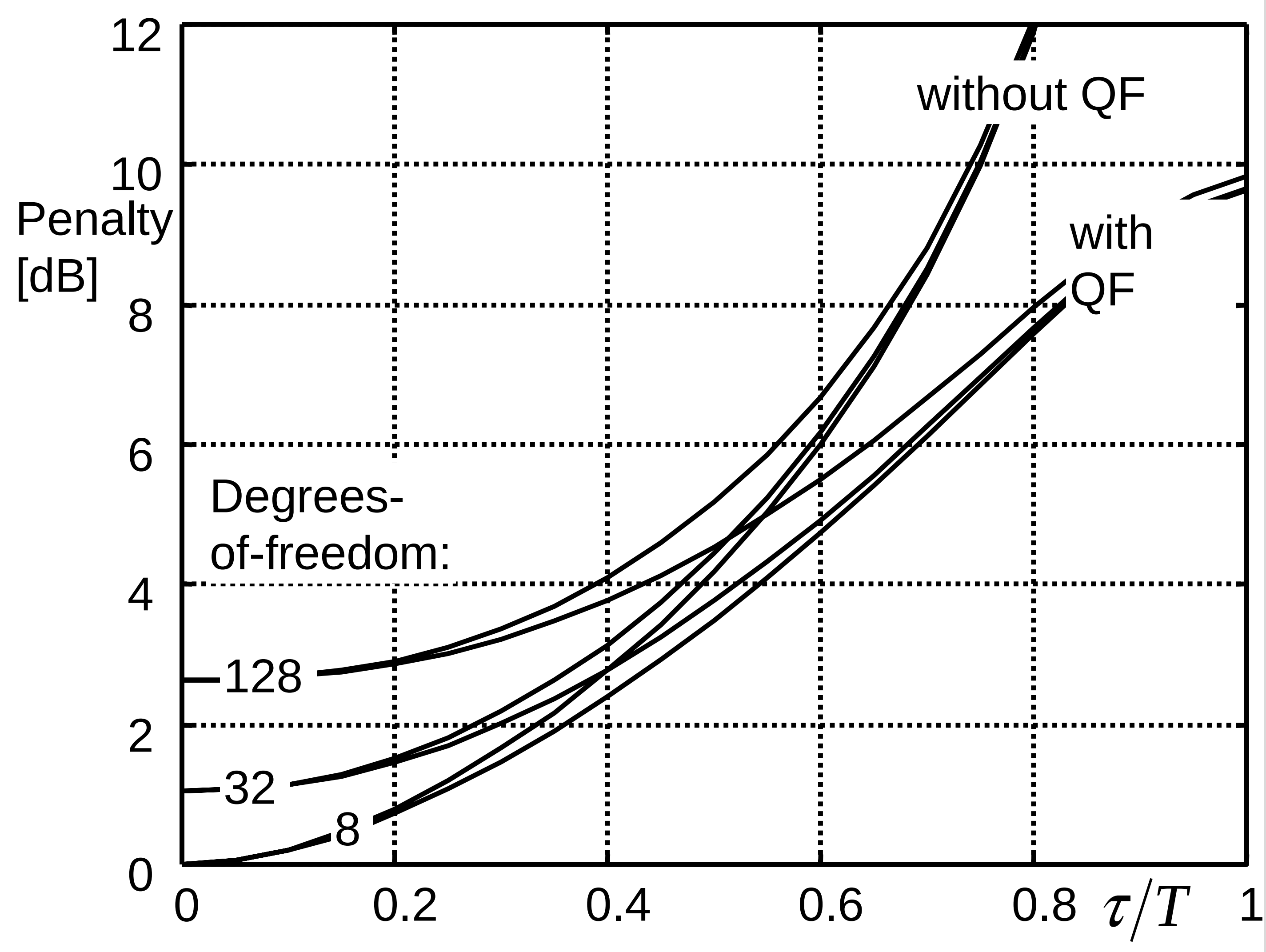
Electrical PMD compensation by quantized feedback



+ = optimum decision point

Due to negative binomial or χ^2 noise from optical amplifiers, system penalty is larger than subdiagram opening penalty.

Calculated sensitivity penalty vs. normalized DGD



Calculation fundamentals: R. Noe, Electrical Engineering 83(1001), pp. 15-20

However

- Experiments have shown smaller penalties.
- Reasons:
  - Noise is not purely negative binomial or χ^2.
  - Finite extinction and unavoidable patterning penalties generally mask the first ~1...2dB of PMD penalty.
- More elaborate equalizers may improve matters.
- Electrical equalizer can help also against other distortions.
- Much cheaper than optical PMD compensators.
- Electrical PMD compensation is an attractive compromise for any bit rate where it can be implemented!

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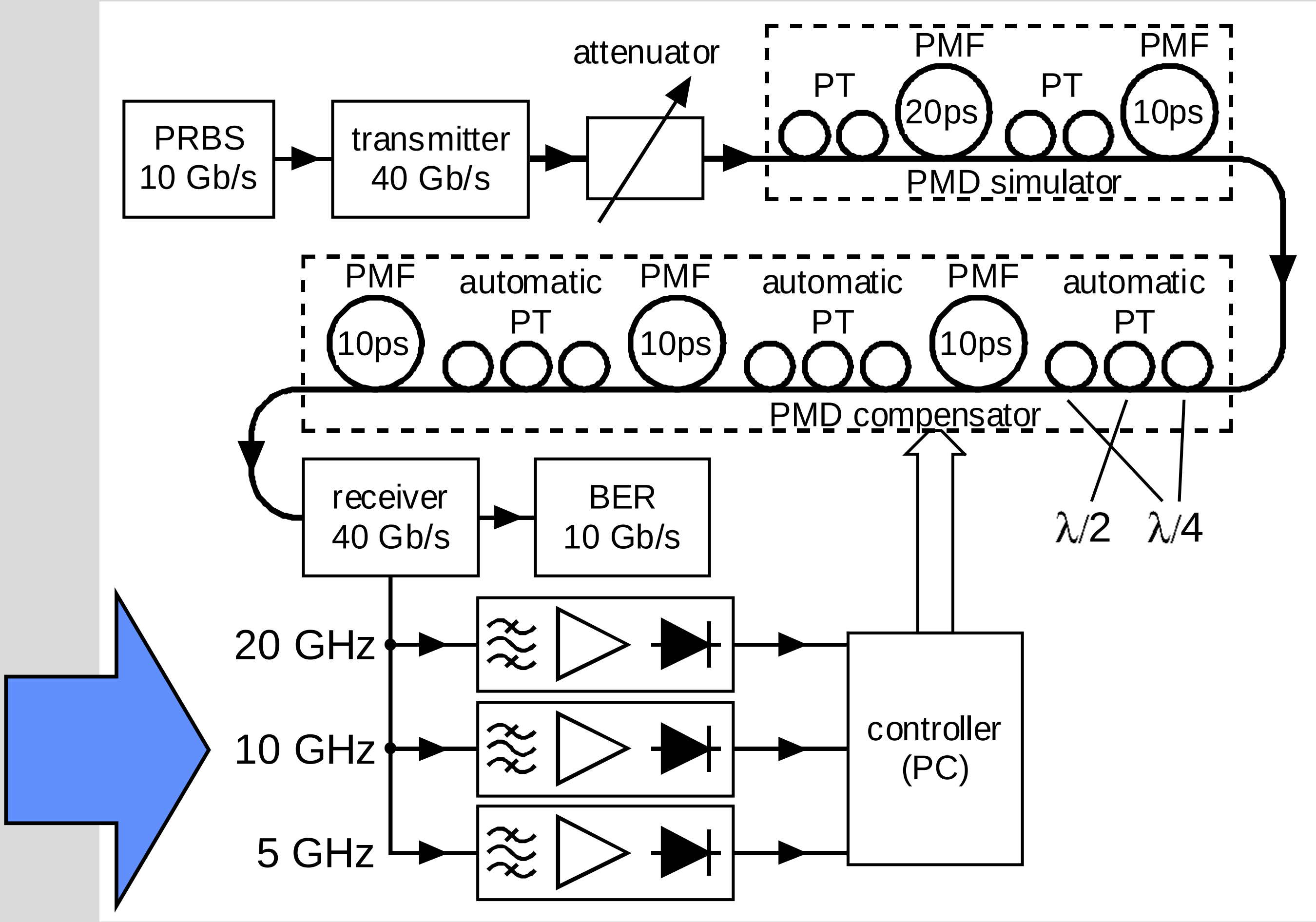
PMD penalty detection by spectral analysis

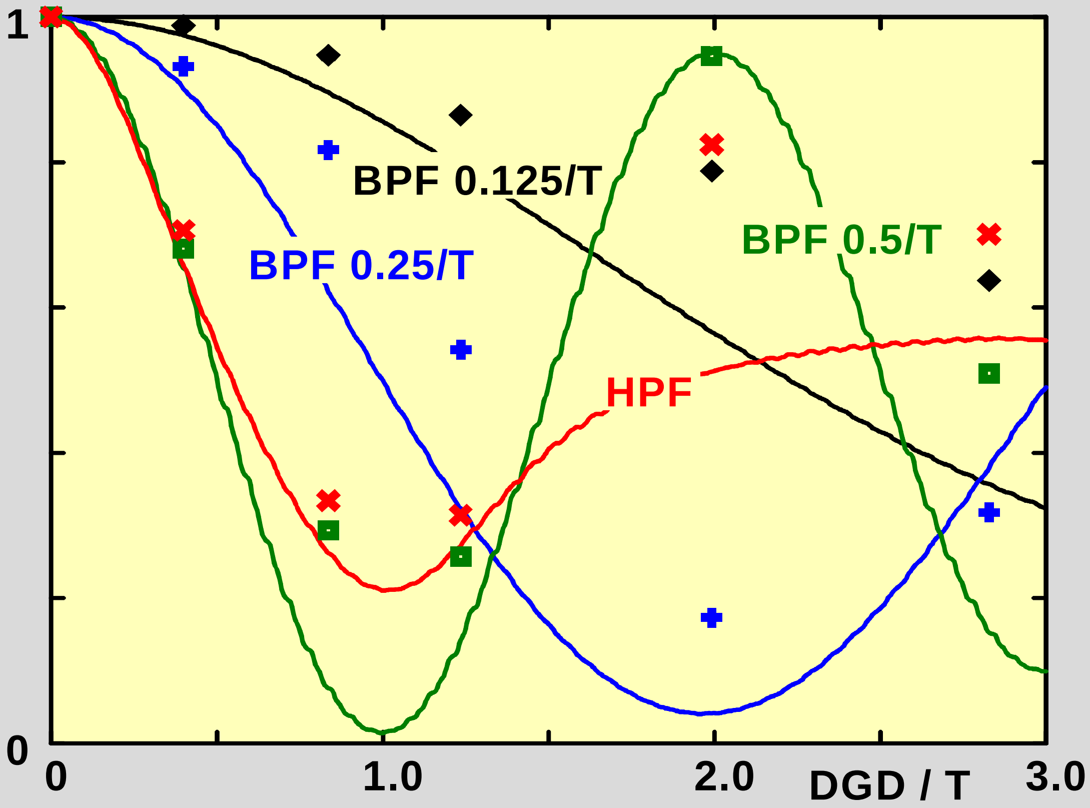


Univ. Paderborn / Siemens, 1998

- Simple realization: Bandpass (or highpass) filter, followed by square-law power detector
- Essentially, the opening is being maximized.
- Example: Filter bandwidth = 4 GHz, initial filter output SNR = 0 dB, integration over 10 µs yields final SNR = 46 dB. Is this sufficent?

Performance of spectral analysis PMD penalty detectors

(Measured at 10Gb/s, but could be scaled to any bit rate.)

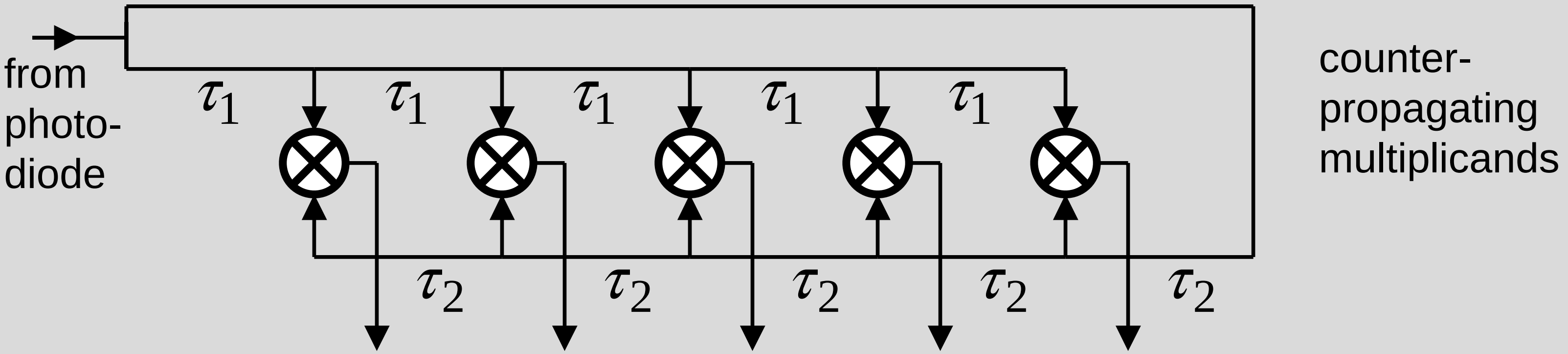


- 5 GHz bandpass filter or 4 ... 10 GHz highpass filter detects PMD most sensitively.
- Unambiguous readout until 400 ps of 1st-order DGD by 2.5 and 1.25 GHz filters
- Switching between, and linear combination of different signals

Autocorrelation function measurement in receiver

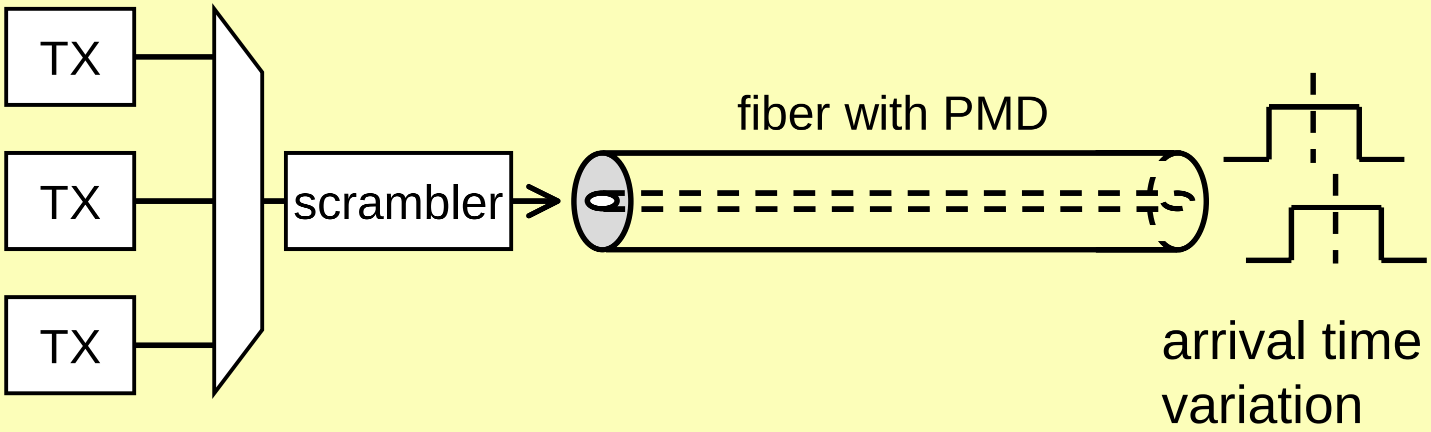
- Good PMD detection requires finely spaced bandpass filters.
- Ideally, the power spectral density should be made $\propto \mathrm{sinc}^2(\omega T/2)\cdot\left|H_{RX}(\omega)\right|^2$, where $H_{RX}(\omega)$ is frequency response of receiver.
- Corresponding autocorrelation function:

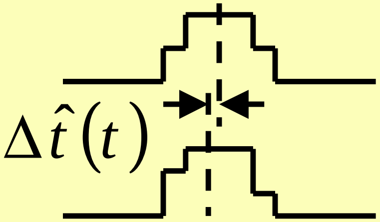
- Battery of multipliers can determine sampled autocorrelation function:



- Co- or counterpropagating multiplicands are possible, sampling period is $\tau_1 \mp \tau_2$.
- PMD compensator must purify measured autocorrelation function.
- Function expected to be very similar to that of bandpass filter bank.
- Advantage: Easier to integrate than filter bank

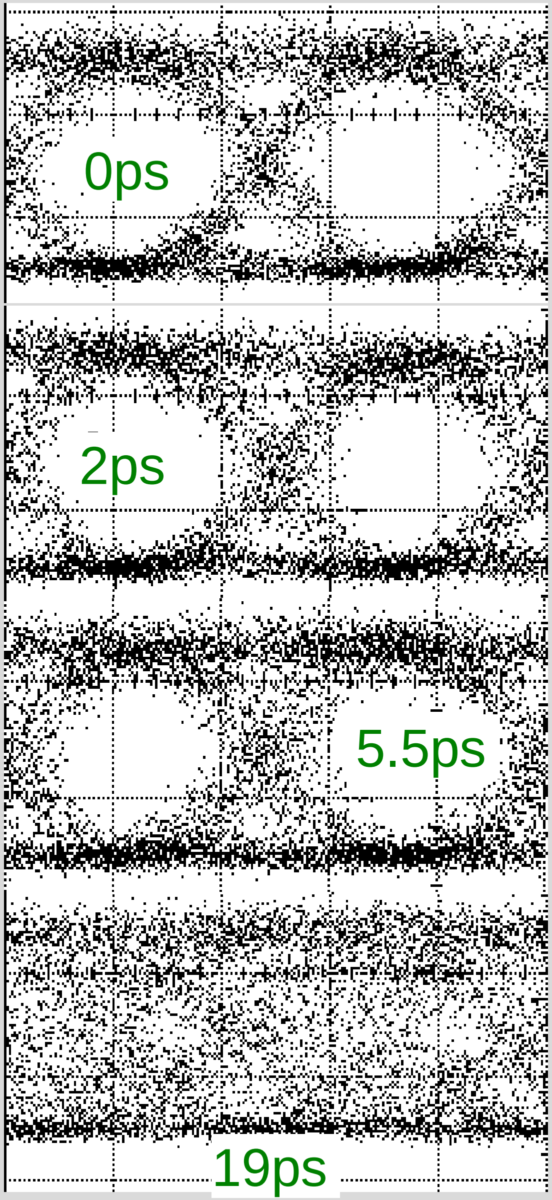
Polarization modulation causes arrival time variations in the presence of PMD



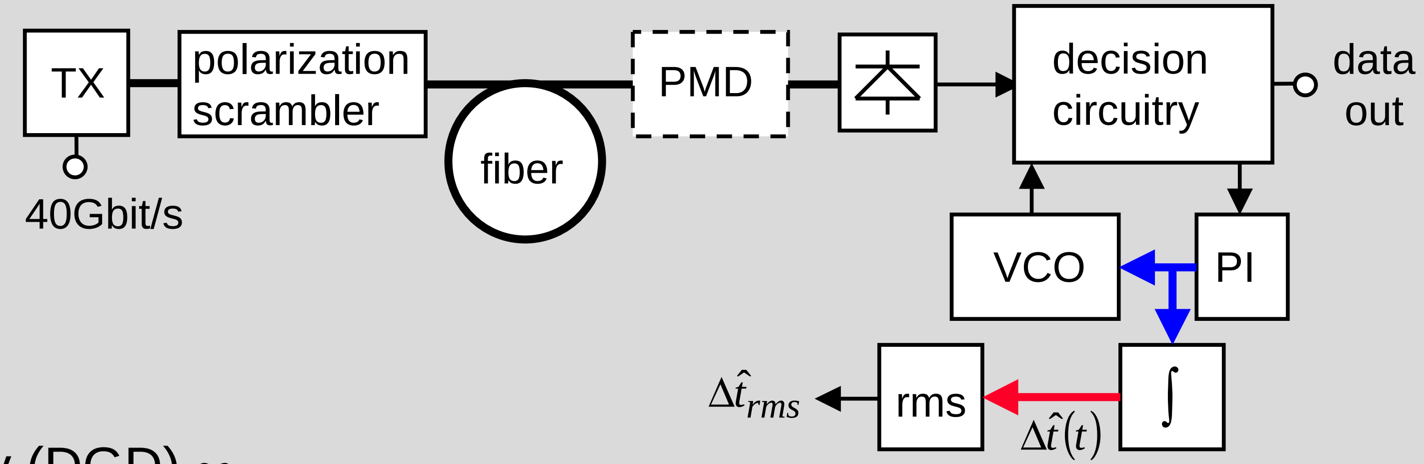


One polarization scrambler may be shared by many wavelength channels.

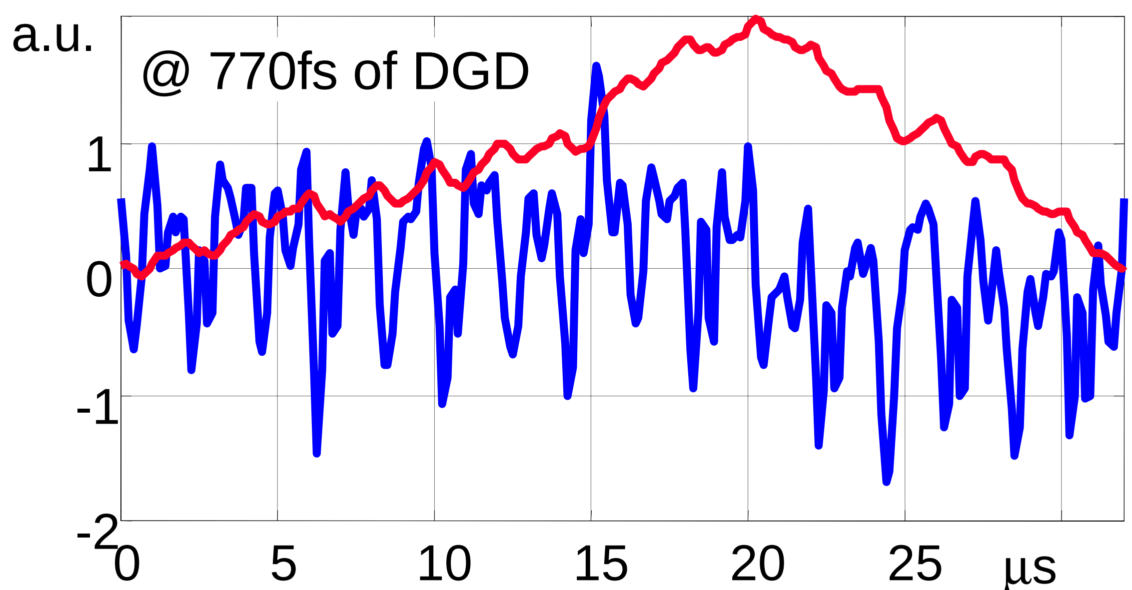
40Gbit/s eye diagrams (triggered from TX)



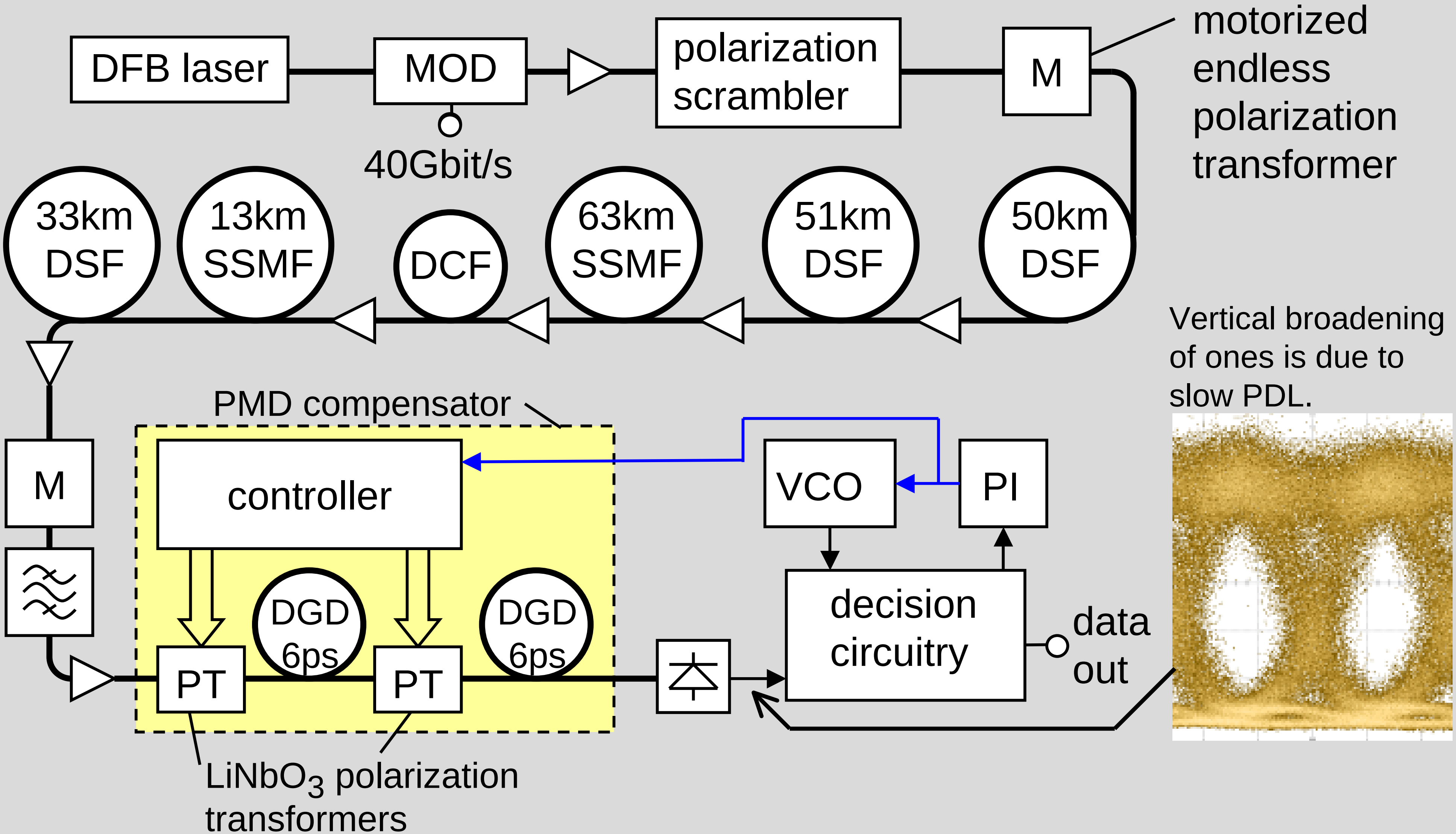
PMD detection in 40Gbit/s transmission system



- Clock recovery PLL in receiver tracks arrival time variations.
- Arrival time ∝ clock phase ∝ integral of VCO input signal
- Differential group delay (DGD) ∝ arrival time variations
- Bit rate scalablity
  - „If you can demultiplex the signal using a clock PLL, then arrival time detection is also possible.“
  - PLL may even include OTDM demultiplexer at high data rates.

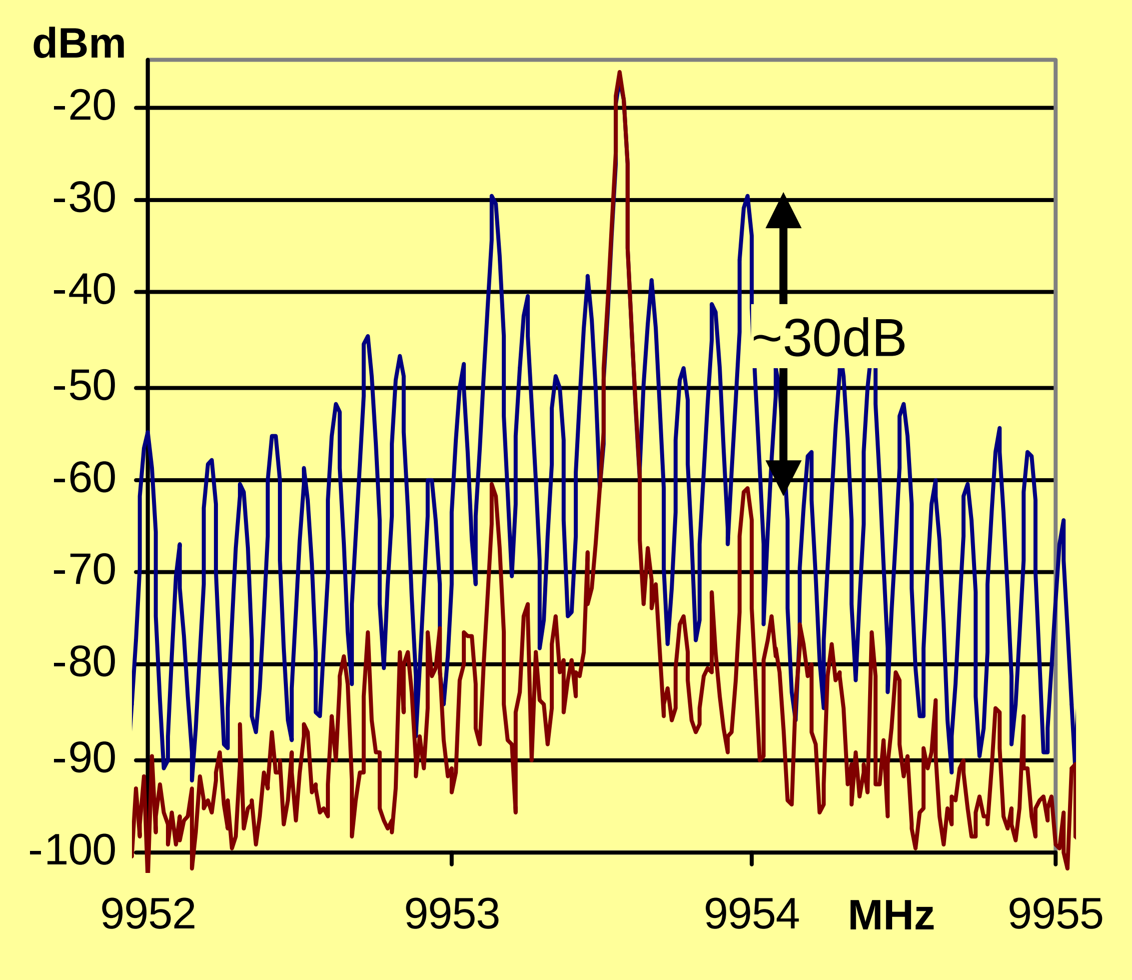


40Gbit/s PMD compensation with arrival time detection



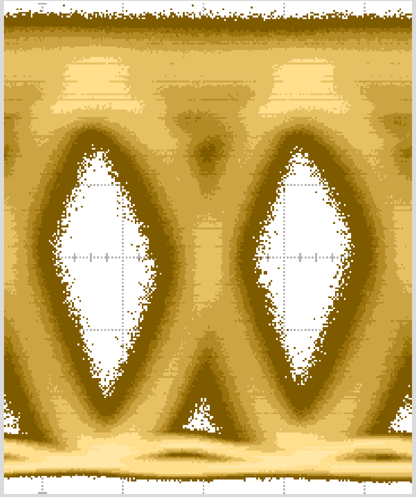
Vertical broadening of ones is due to slow PDL.

Prescaled clock spectra in the presence of a 19ps DGD



without PMD compensation

with 10ps + 8.5ps PMD compensator



10min persistence, rotating emulator

Root mean square arrival time variation vs. differential group delay for „tennis ball“ polarization scrambler

$\Delta\hat{t}_{rms}(0\text{ps}) + \sigma < \Delta\hat{t}_{rms}(\text{sensitivity}) - \sigma$

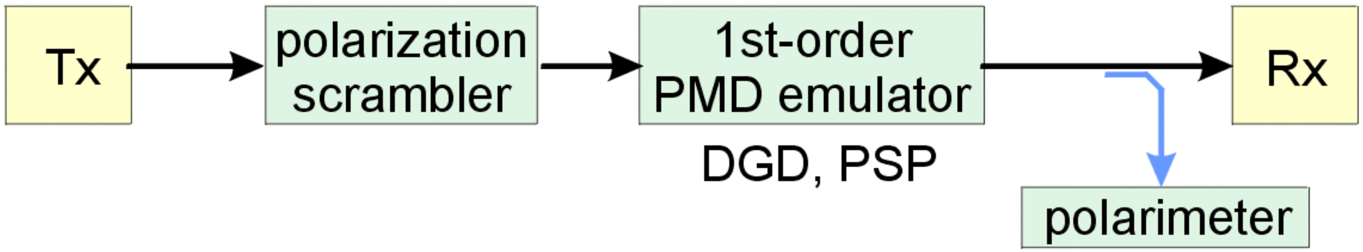
$\Rightarrow$ 0.88ps or 1.35ps sensitivity

2.4µs measurement interval (417kHz scrambling frequency)

3-Dimensional DOP-Evaluation

courtesy
Rosenfeldt et al., ECOC 2001

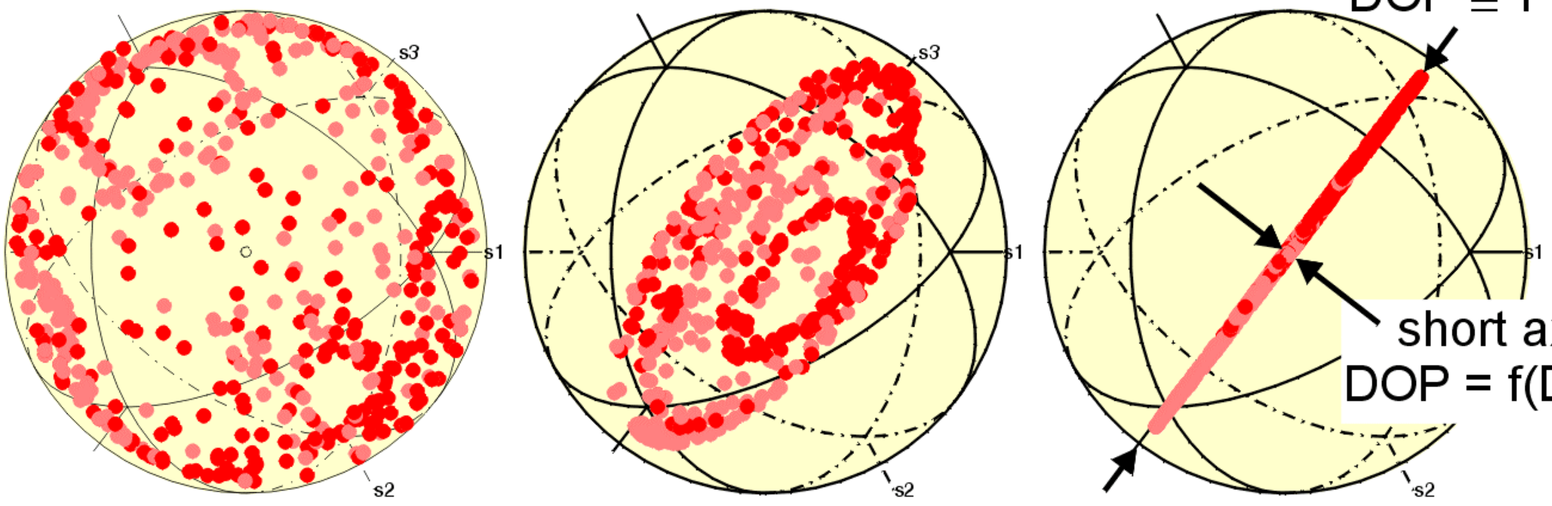
experimental setup at 40 Gbit/s RZ:


Tx → polarization scrambler → 1st-order PMD emulator → Rx

DGD, PSP

polarimeter

received SOPs form an ellipsoid:



long axis
DOP ≅ 1 ⇒ PSP

short axis
DOP = f(DGD)

DGD= 0 ps

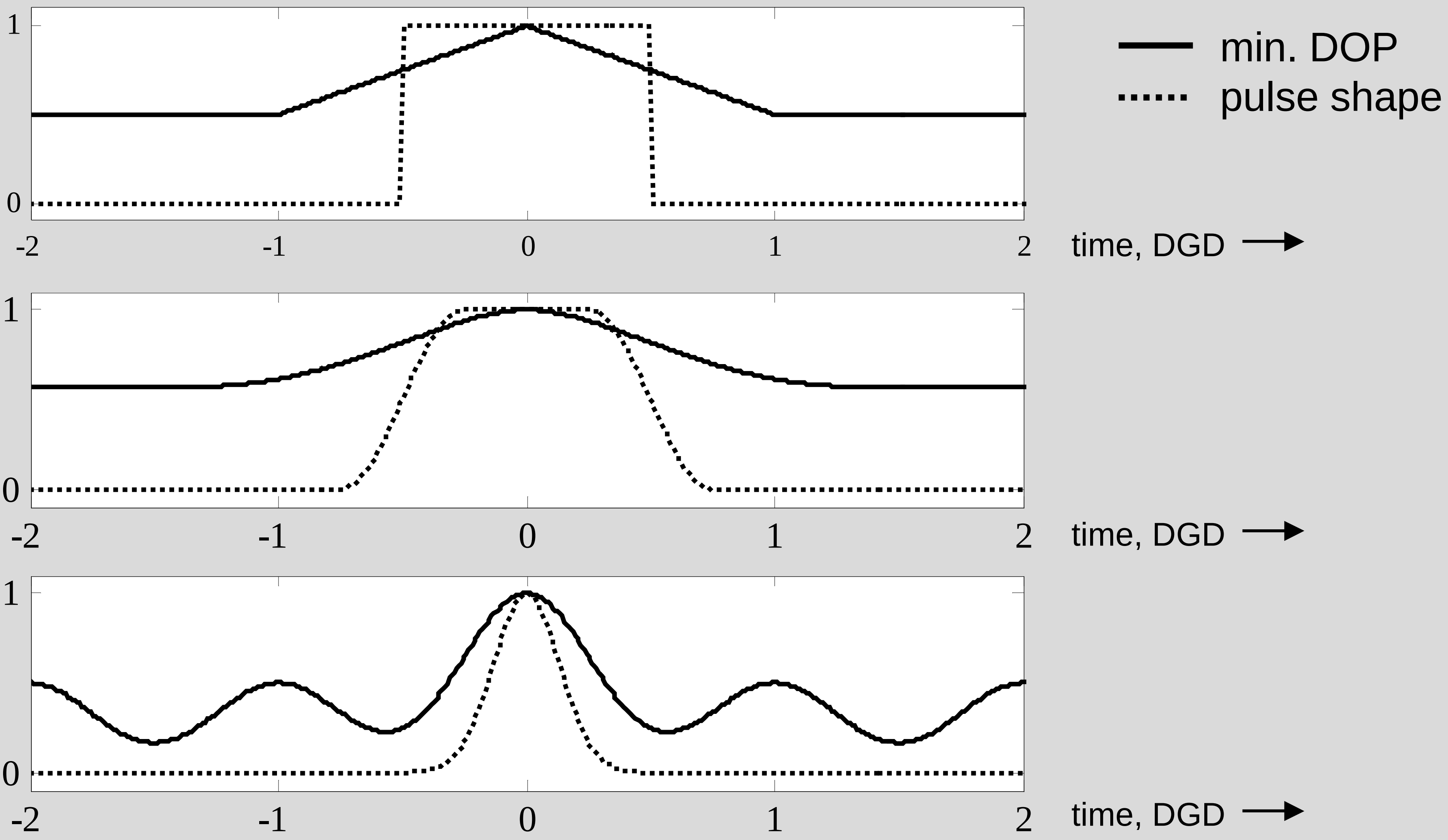
DGD= 1.25 ps

DGD= 8 ps

Polarimetric PMD detection

- Scalable to any bit rate !
- DOP measurement introduced by N. Kikuchi, S. Sasaki, ECOC 1999.
- Improvement by scrambler and by making use of the measured polarization states (H. Rosenfeldt et al., OFC2001).
- Allows for direct control of PMD compensator (but only if polarization transformations between polarimeter and PMD compensator are known and stable!)
- Higher-order PMD detection is likewise possible.
- Drawbacks: Cost, ambiguity (for RZ)
- Possible remedies:
  - Grating-based spectral polarimeters (P. Westbrook et al., OFC2002, WK5)
  - Extra optical filters

Minimum DOP vs. DGD for different pulse shapes



Readout is proportional to DGD, but only if pulses edges are shorter than DGD !

How to detect 1st-order PMD

Measurement of	**eye opening**	**power spectral density (or auto-correlation funct.)**	**arrival time detection**	**polarimetric methods**
Polarization scrambler needed	no	no	yes	no**
Extra optics in each WDM channel	no	no	no	no**
Extra RF electronics	yes	yes	no	no
Readout is $\propto \mathrm{DGD}^n$, $n =$	2	2	1	1*
Speed	slow	fast	fast	fast**

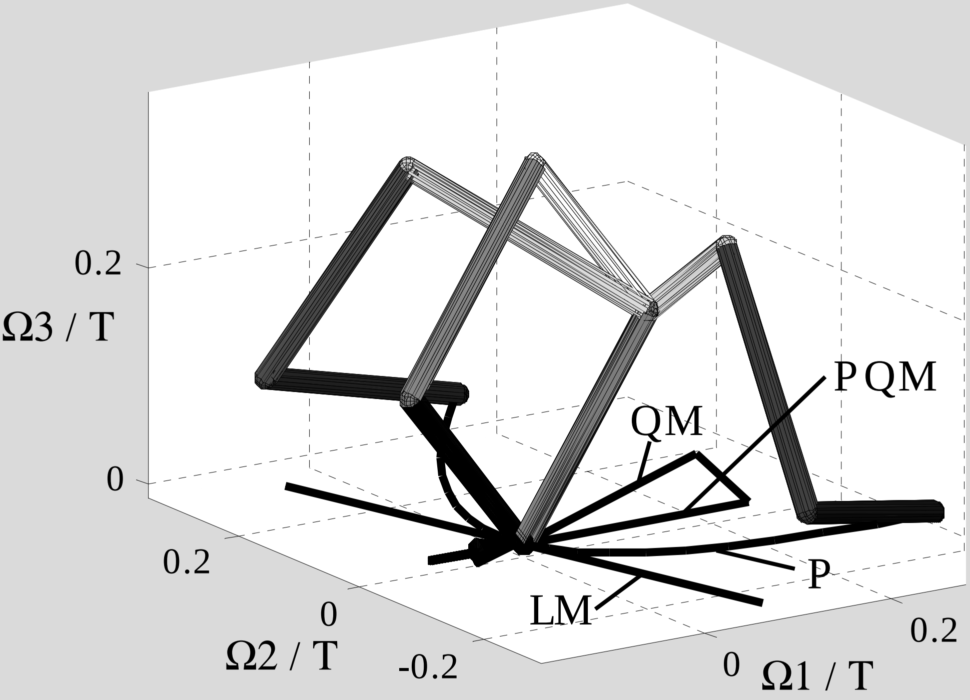
* as long as pulse rise and fall times are shorter than DGD

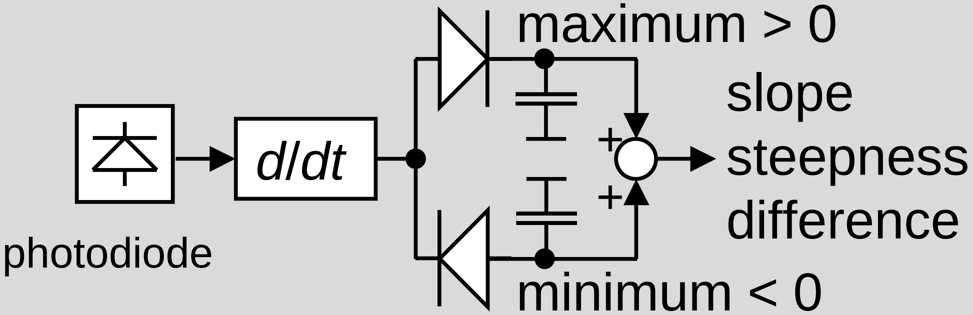
** in principle

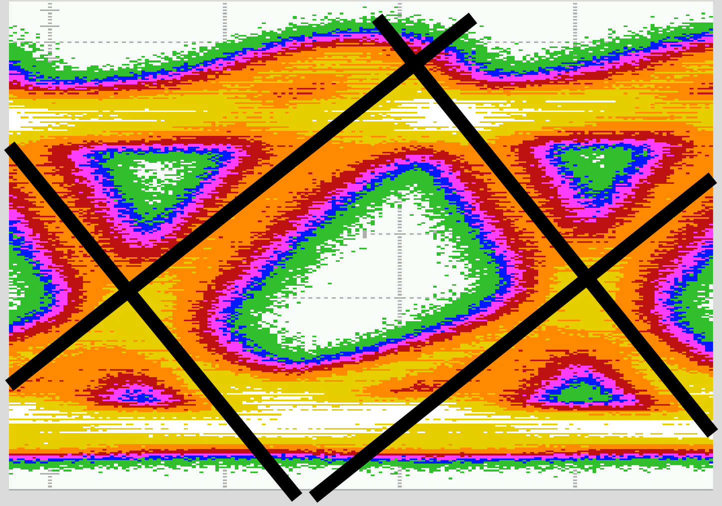
<u>Arrival time detection is easily realized with commercially available technology.</u>

Slope steepness difference indicates higher-order PMD

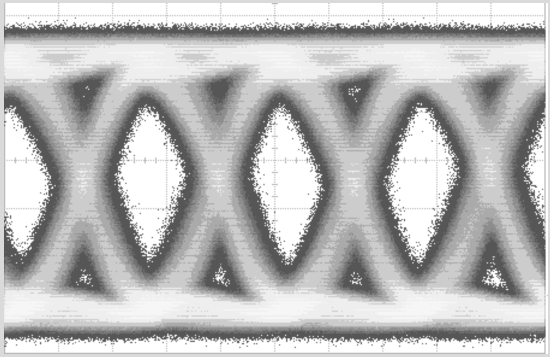
- Assuming perfect arrival time detection, resulting DGD profile of fiber and PMD compensator will most likely form a loop.
- As a function of optical frequency, sections with given constant DGDs twist, thereby sliding loop endpoint on a parabola P.
- Projection PQM of quadratic motion QM (parabola ordinate) along input polarization causes eye diagram shear.
- Slope steepness difference variations always exists due to scrambling.



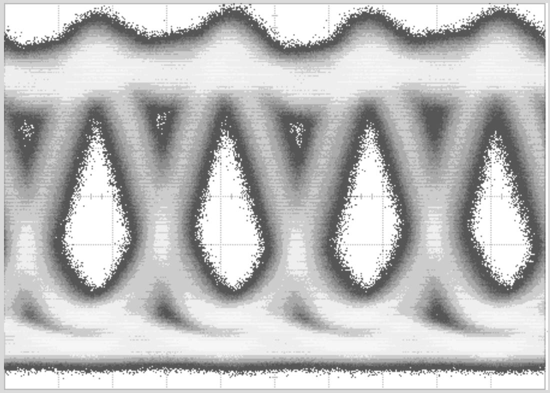




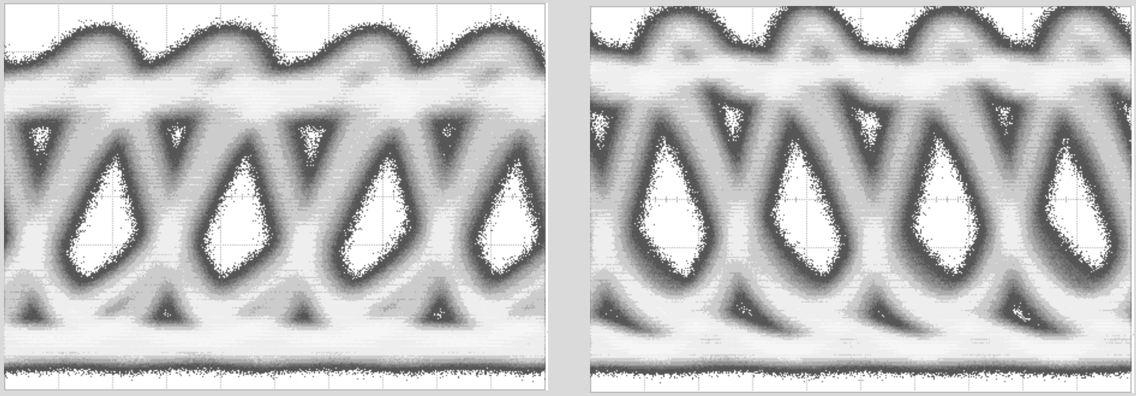
Effects of DGD loop on 40Gbit/s eye diagram



Back-to-back

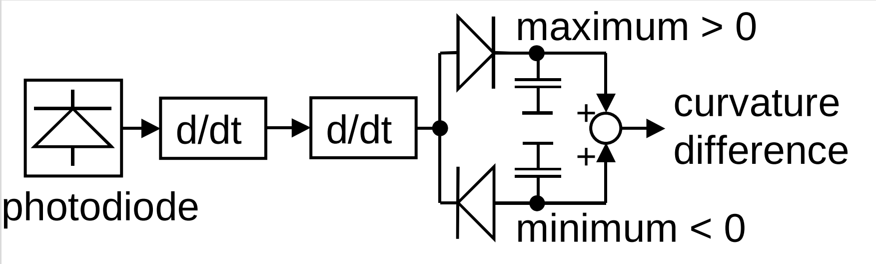


Input polarization parallel to linear motion of DGD profile endpoint.

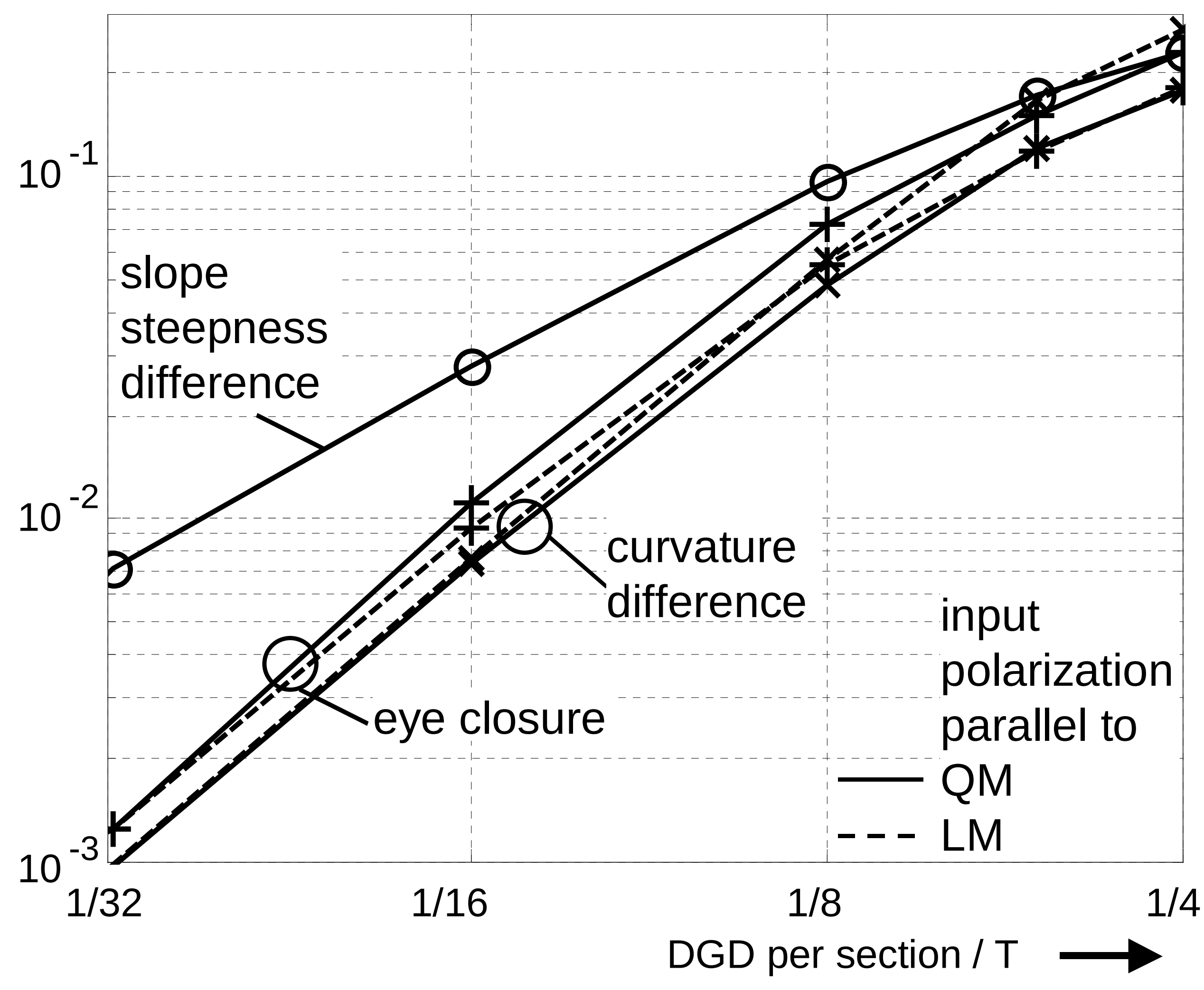


Input polarization parallel to quadratic motion of DGD profile endpoint.

- Curvature difference (like for chromatic dispersion) always exists.
- Measurement:



Detectability of square-shaped DGD „loop“ vs. section length



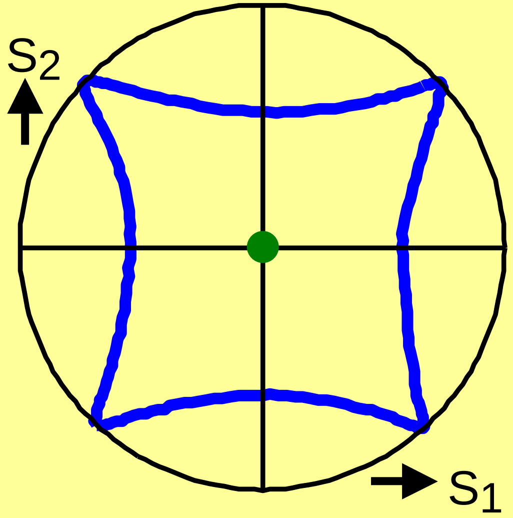
- Slope steepness difference is most sensitive for small DGDs.
- Readout is proportional to DGD loop area.
- Polarization scrambling is required but this may have been implemented for 1st-order PMD detection anyway.

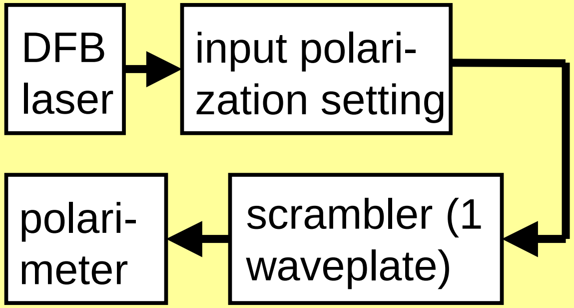
How to detect DGD loop for any input polarization

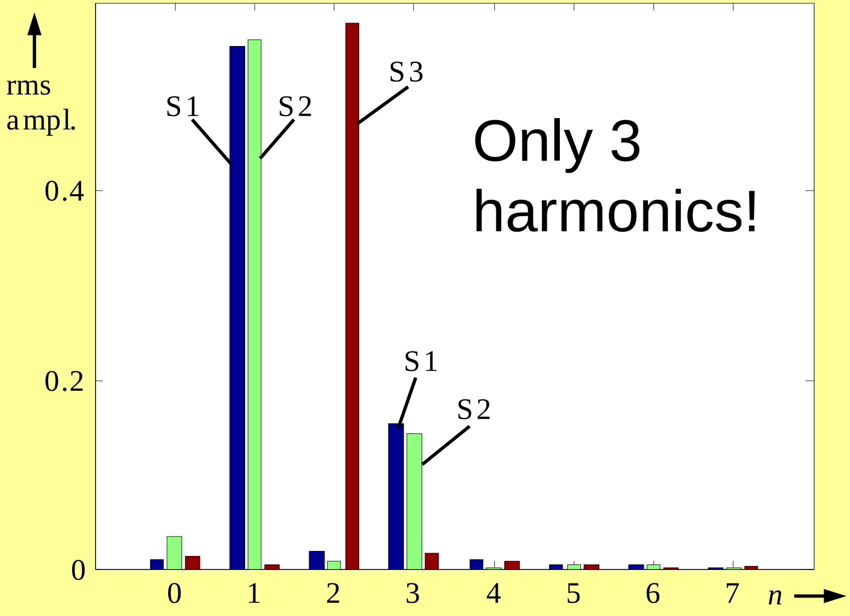
Measurement of	**eye opening**	**highpass output power**	**curvature difference**	**slope steepness difference**
Detects PMD of order	1, 2, 3	1, 2, and, with wrong sign, 3	2, 3	3
Readout is $\propto \mathrm{DGD}^n$, $n =$	3	ambiguous readout (see above)	3	2
Hardware effort	highest	low	higher	low
Speed	slow	fast	fast	fast
Patterning	strong			weak
Polarization scrambler needed?	no			yes
Influence of fiber chromatic dispersion (CD)	polarization-dependent addition of 2nd-order PMD and fiber CD			decreases readout

Slope steepness difference (+ highpass output power) measurement is attractive.

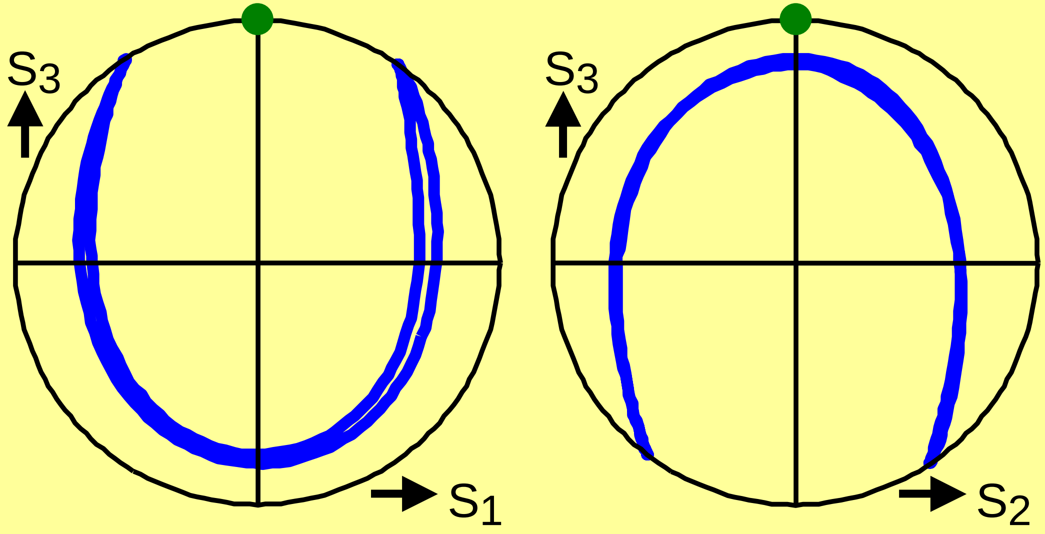
Electrooptic „tennis ball“ polarization scrambler: Measured output Stokes parameter trajectories and spectra




DFB laser
input polarization setting
scrambler (1 waveplate)
polarimeter

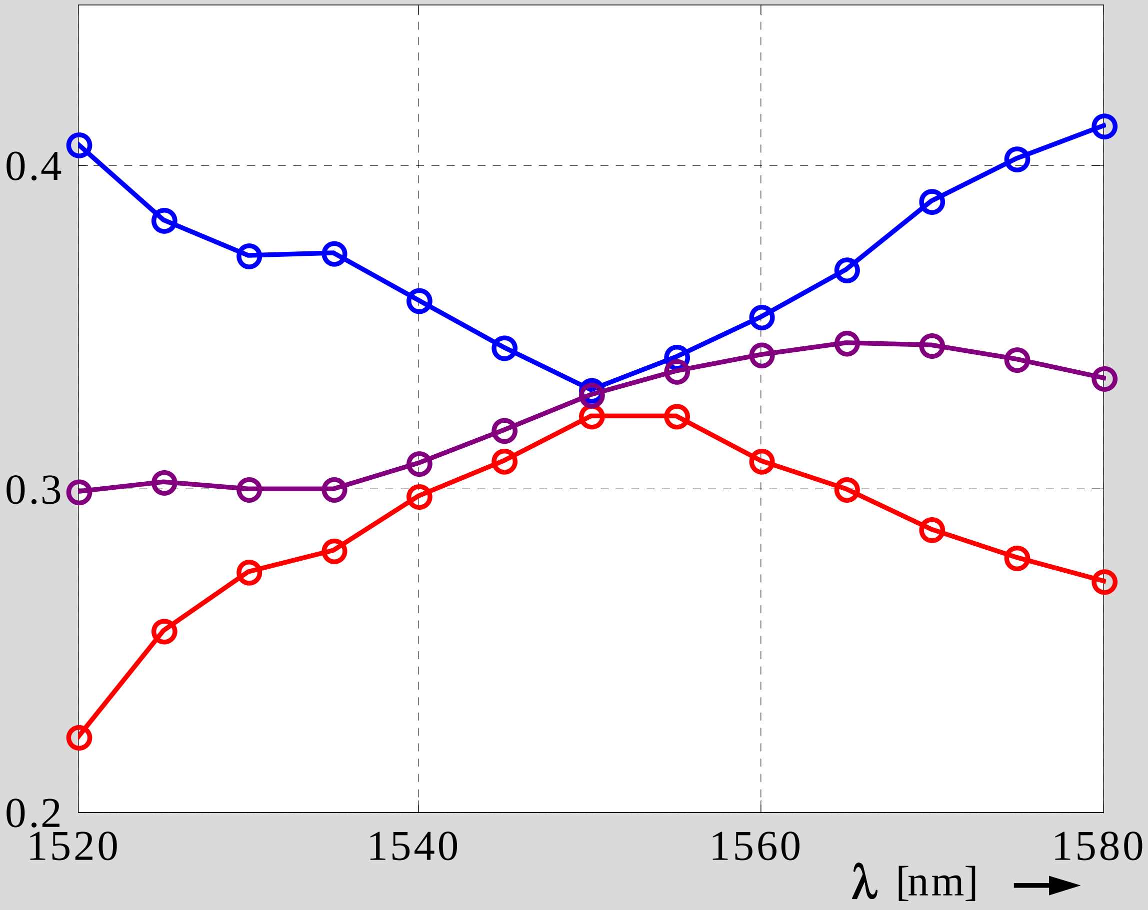


Only 3 harmonics!



- Circular input polarization
- $$\mathbf{S} = \begin{bmatrix} \left(1+\sqrt{1/3}\right)/2 \cdot \cos \omega t - \left(1-\sqrt{1/3}\right)/2 \cdot \cos 3\omega t \\ \left(1+\sqrt{1/3}\right)/2 \cdot \sin \omega t + \left(1-\sqrt{1/3}\right)/2 \cdot \sin 3\omega t \\ \sqrt{2/3} \cdot \cos 2\omega t \end{bmatrix}$$
- Eigenvalues of Stokes vector covariance matrix: 1/3 ± 0.0055

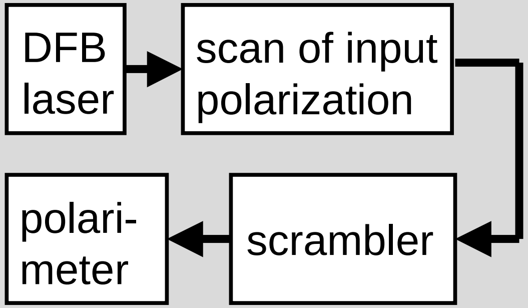
Eigenvalues of normalized Stokes vector covariance matrix for tennis ball polarization scrambler



- Convergence speed of optical PMD compensation with arrival time detection depends on eigenvalues.
- Variations are permissible as long as minimum convergence speed (for most infavorable polarization setting) is sufficiently fast.

at least 4THz usable bandwidth

Covariance matrix eigenvalues of polarization-independent 2-waveplate polarization scrambler

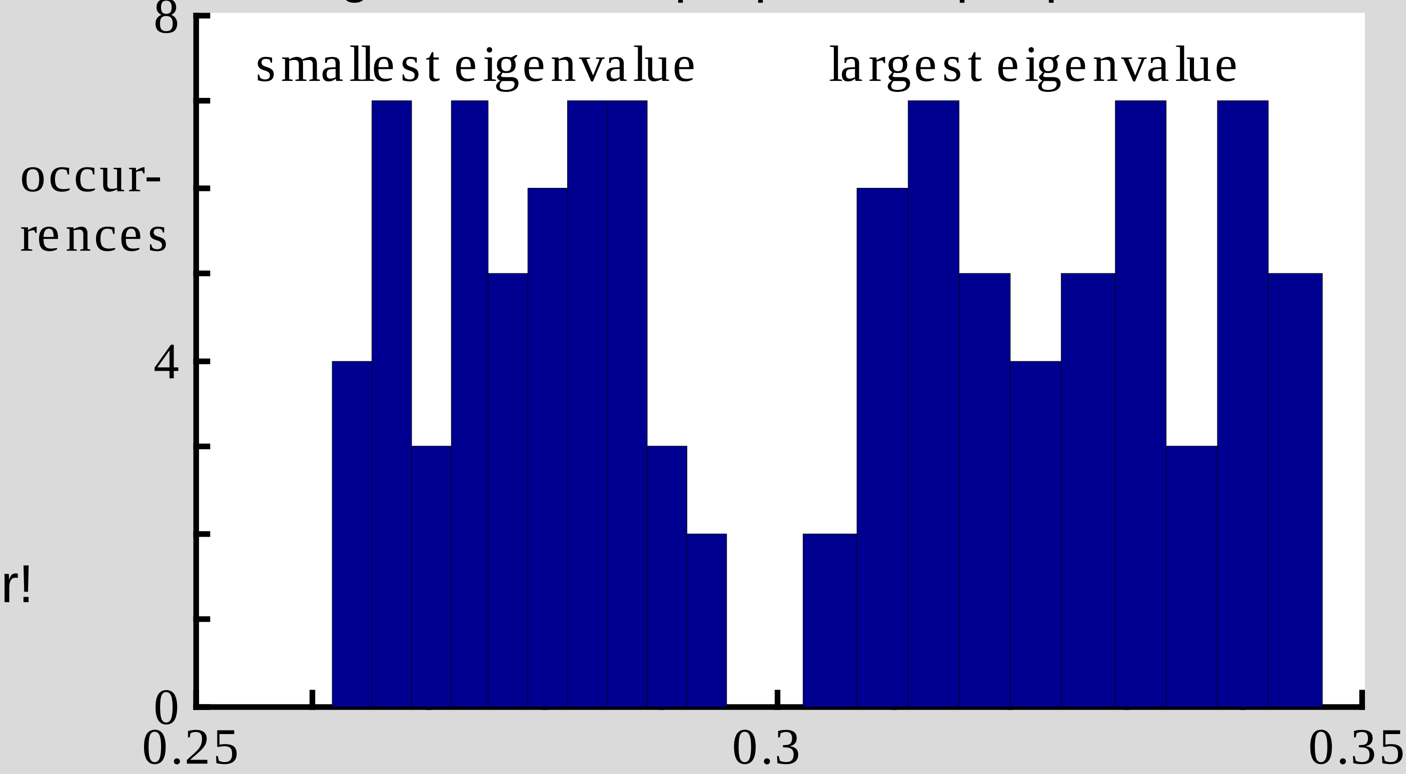

DFB laser

scan of input polarization

scrambler

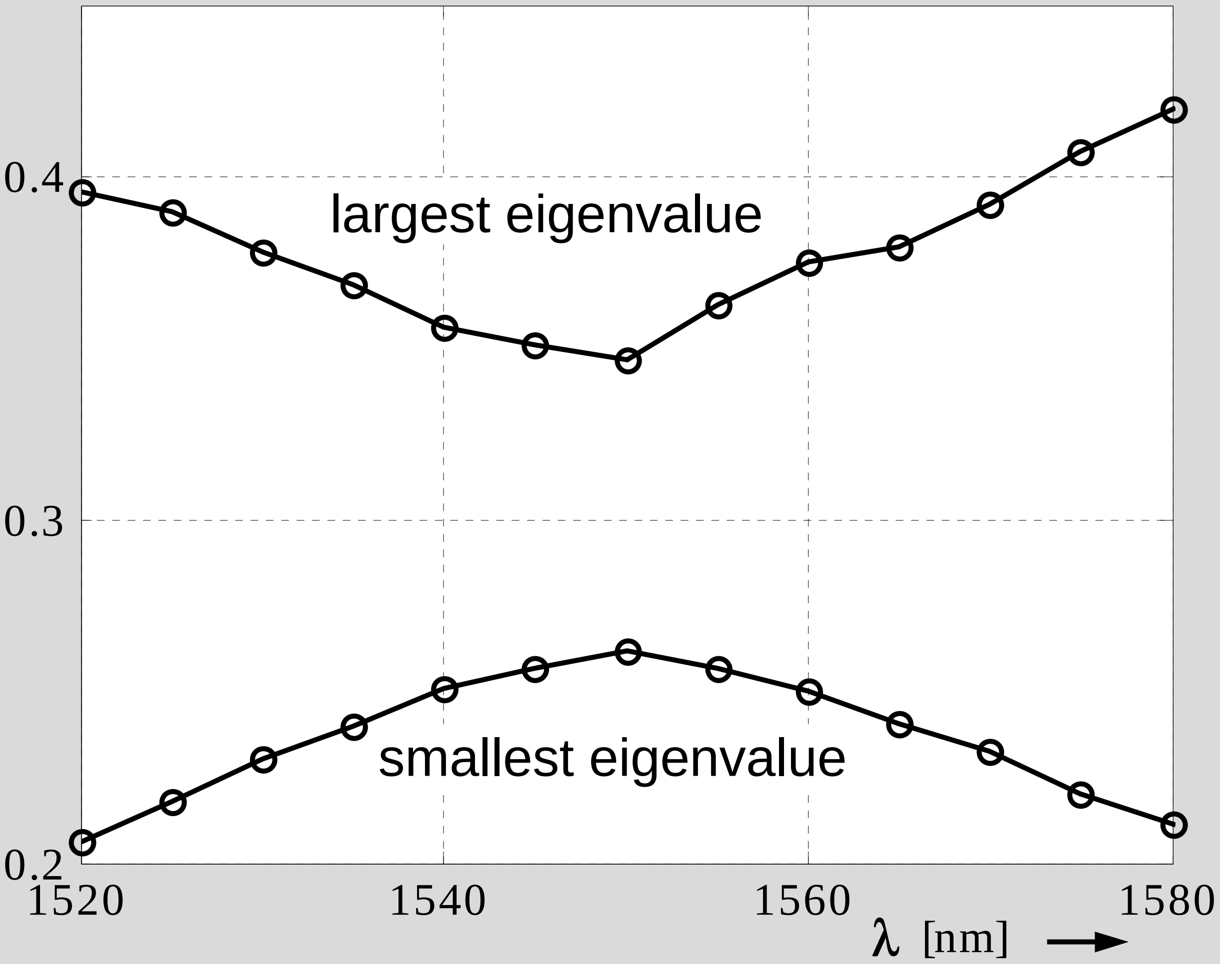
polari-meter

histogram for 51 equispaced input polarizations



- Higher harmonic content than tennis ball scrambler!

Covariance matrix eigenvalues of polarization-independent 2-waveplate polarization scrambler



Values taken for scan over 51 equidistributed input polarizations

~4THz usable bandwidth

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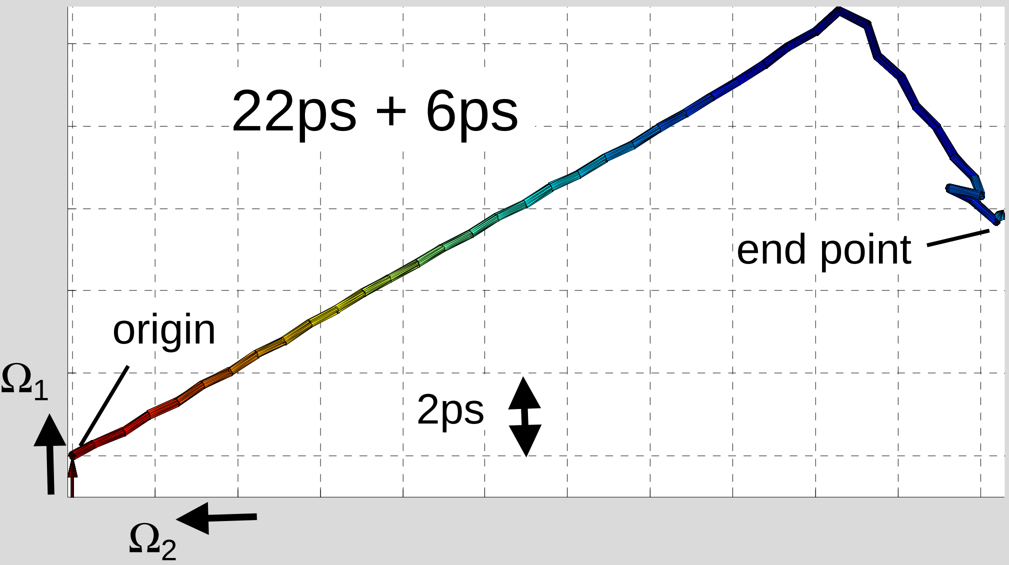
Differential group delay profiles are determined by inverse scattering. – Task of ideal PMD optical compensation.

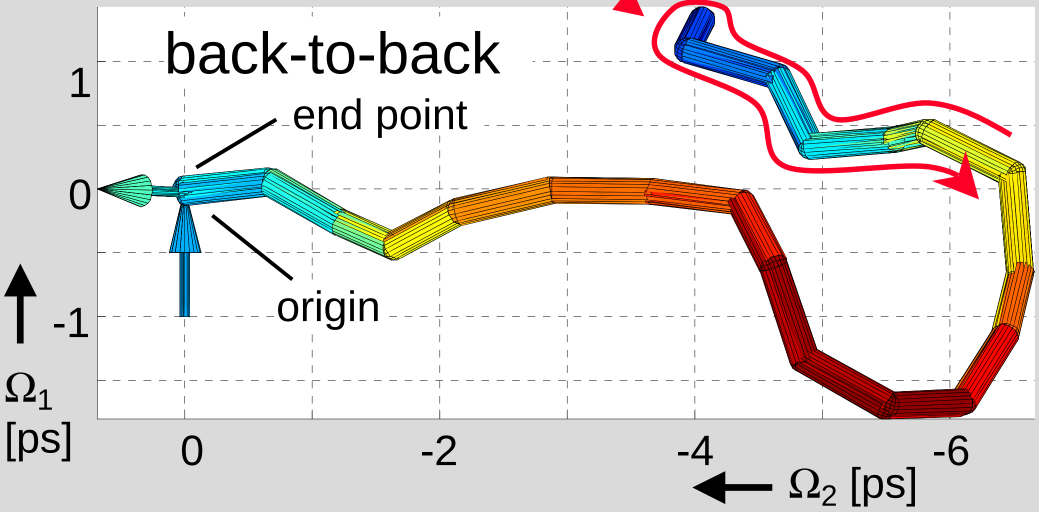
PMD vector of two cascaded DGD sections: $\mathbf{\Omega} = \mathbf{\Omega}_{c,1} + \mathbf{R}_1^{-1}\mathbf{\Omega}_{c,2}$

PMD vector of many cascaded DGD sections: $\mathbf{\Omega} = \sum_{i=1}^{n}\left(\left(\prod_{j=1}^{i-1}\mathbf{R}_j^{-1}\right)\mathbf{\Omega}_{c,i}\right)$

DGD profile: concatenated summands of overall PMD vector $\mathbf{\Omega}$

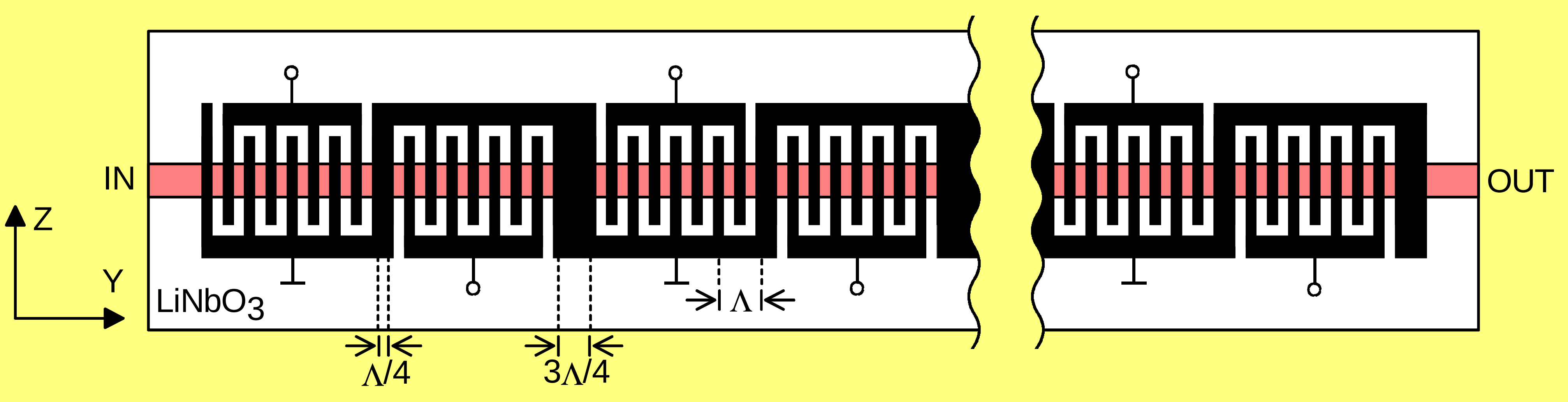


Same as for a fiber plus a perfect PMD compensator, which returns on fiber DGD profile until origin!



Inverse scattering theory proposed by L. Möller

Principle of in-phase and quadrature mode converter in X-cut, Y-propagation $LiNbO_3$

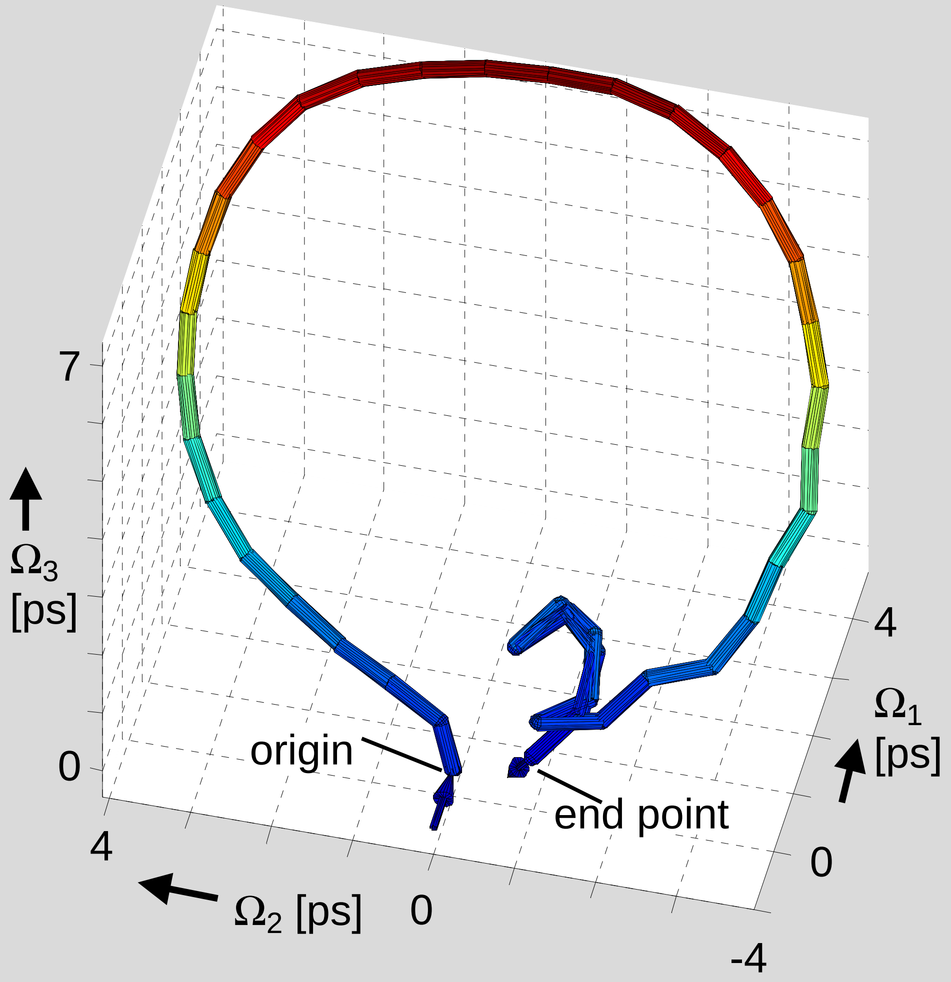


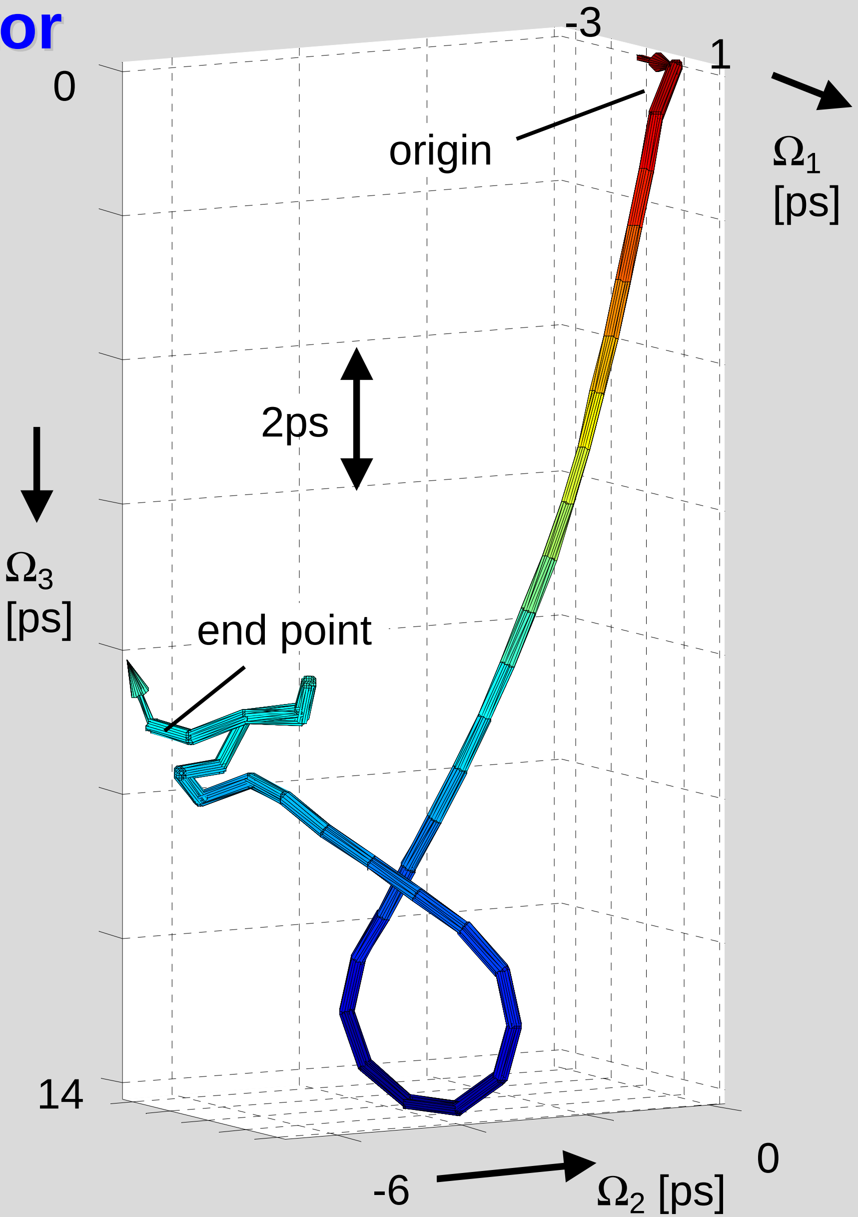
Jones matrix of a waveguide section

$$\begin{bmatrix} \cos\varphi/2 & je^{-j\,\mathrm{arc}(\kappa_1+j\kappa_2)}\sin\varphi/2 \\ je^{j\,\mathrm{arc}(\kappa_1+j\kappa_2)}\sin\varphi/2 & \cos\varphi/2 \end{bmatrix} \text{ with retardation } \varphi = 2m\sqrt{\kappa_1^2+\kappa_2^2}$$

in phase :	**κ_1 linear mode coupling with ±45°**
quadrature:	**κ_2 with right/left circular eigenmodes**
m:	**number of comb fingers in phase and quadrature**

Measured differential group delay profiles of distributed PMD compensator





Advantages of $LiNbO_3$ over other polarization transformers

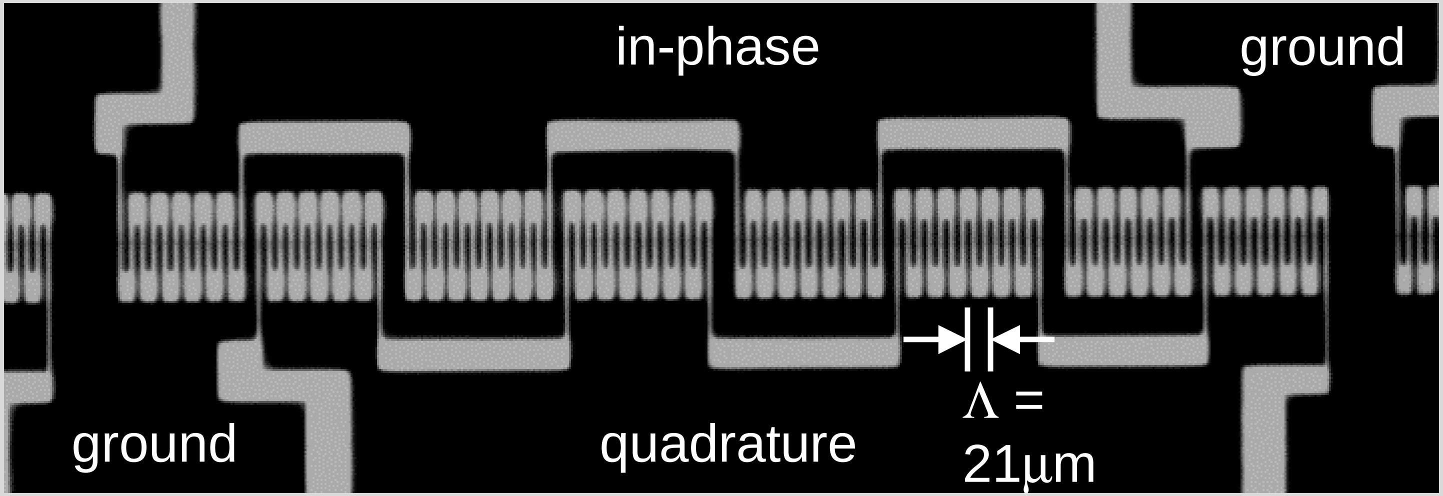
- Speed
- Availability of 2 „kinds“ of birefringence (in-phase and quadrature mode conversion, or phase shift and mode conversion)

Advantages of distributed X-cut, Y-propagation PMD compensator over commercially available X-cut, Z-propagation $LiNbO_3$ polarization transformers

- Low-loss integration of DGD sections and polarization transformers on one chip. Multi-section PMD compensators must have fixed DGD sections anyway (Noé et al., JLT 1999).
- DGD of ~26ps/100mm is perfect at 40...80Gbit/s !
- First and higher-order PMD compensation on one chip !
- Higher electrooptic coefficient
- Polarization transformers are optimally oriented with respect to DGD sections ! (Endless polarization transformation from any polarization to linear in only one X-cut, Z-propagation $LiNbO_3$ waveplate is practically impossible.)
- No, or at least a substantially reduced DC drift !

Fabricated by
Prof. Sohler,
Univ. Paderborn

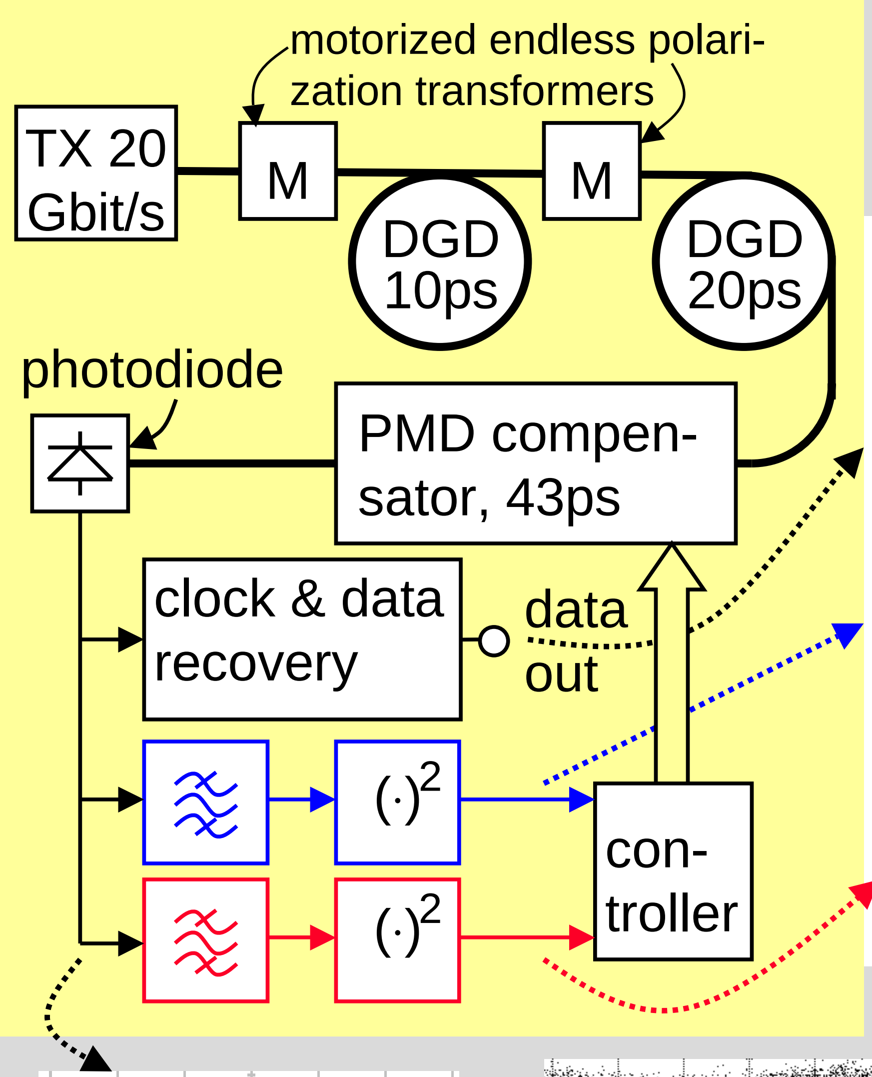
Distributed PMD compensator in X-cut, Y-propagation $LiNbO_3$

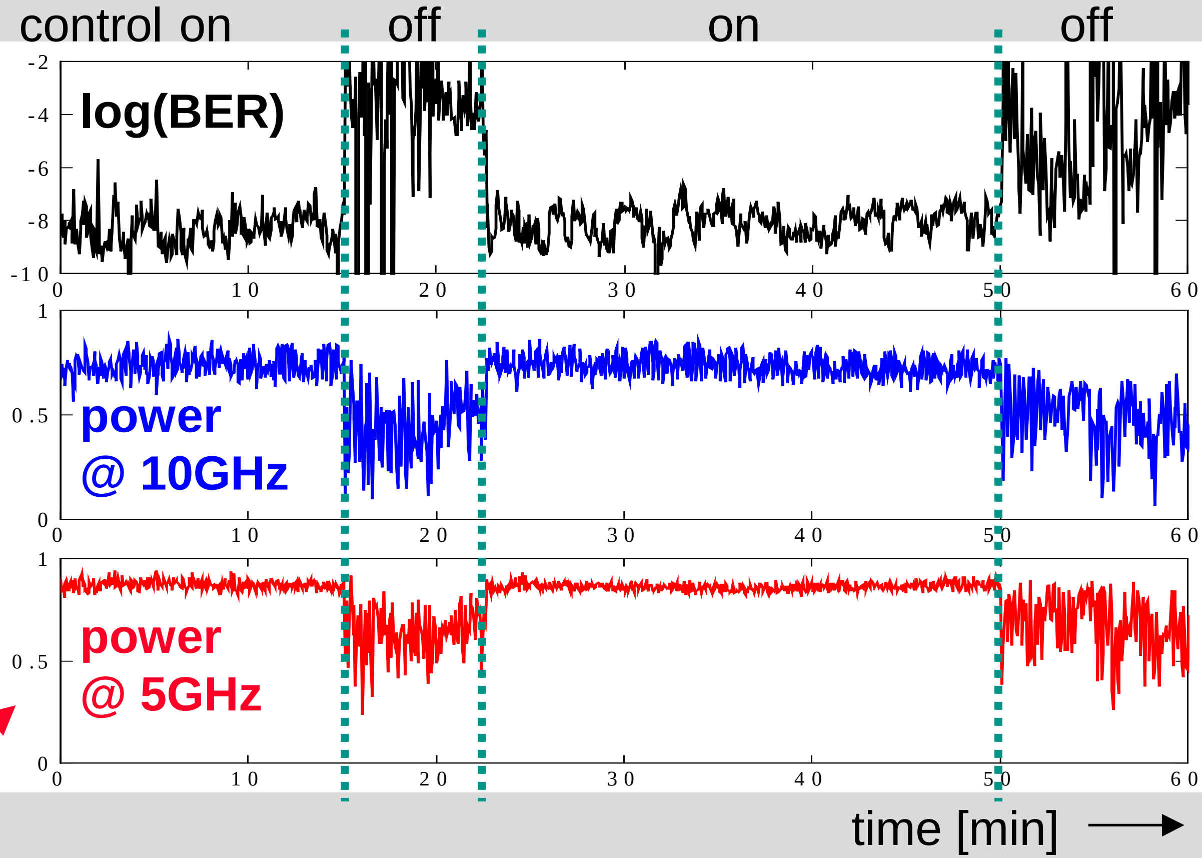


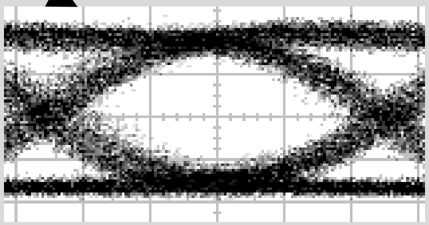
- Optical bandwidth ~3 THz
- Thermal tuning ~100 GHz/K
- Voltages <80V
- 73 electrode pairs (~1.25 mm) on 93 mm long substrate
- Combined differential group delay of 2 units: 43 ps

Experiment performed with Siemens ICN

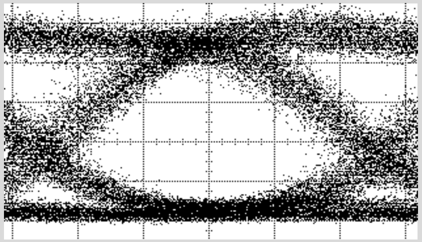
20Gbit/s PMD compensation with distributed PMD compensator



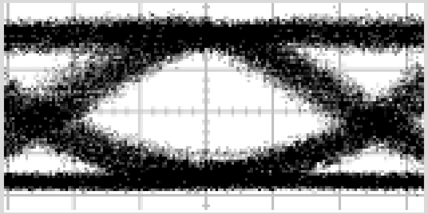




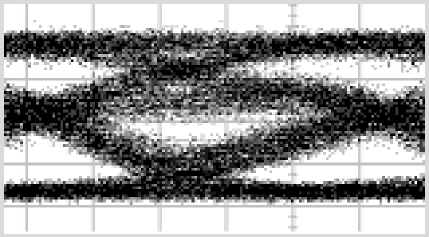
back-to-back



compensator alone



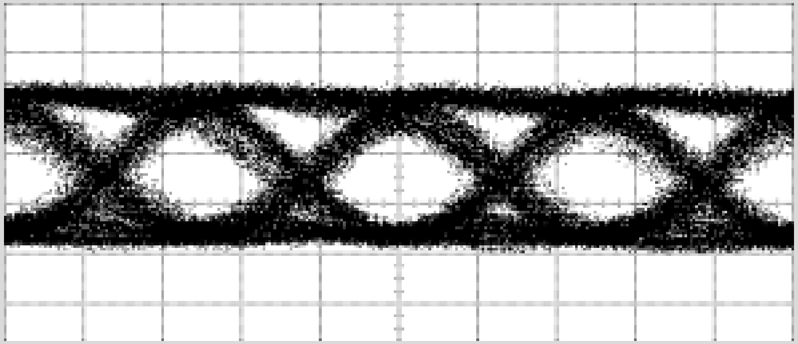
30 ps compensated



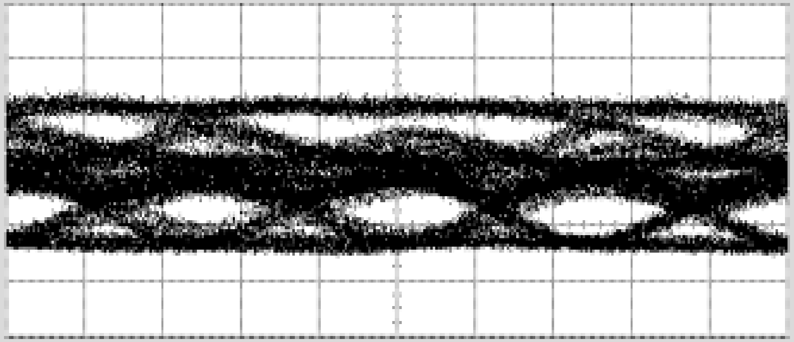
30 ps, compensator off

Experiment performed with Siemens ICN

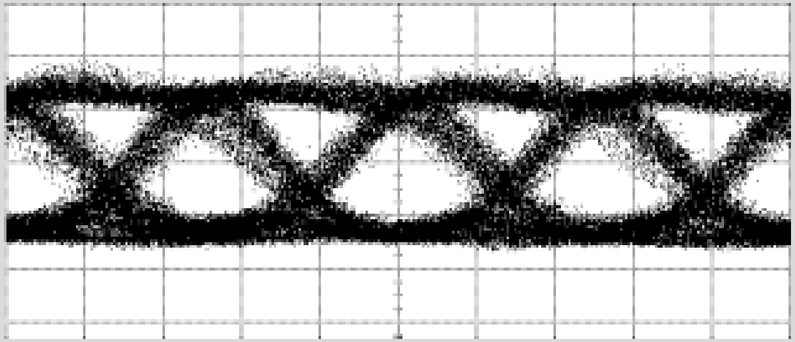
40 Gbit/s eye diagrams with LiNbO$_3$ distributed PMD compensator



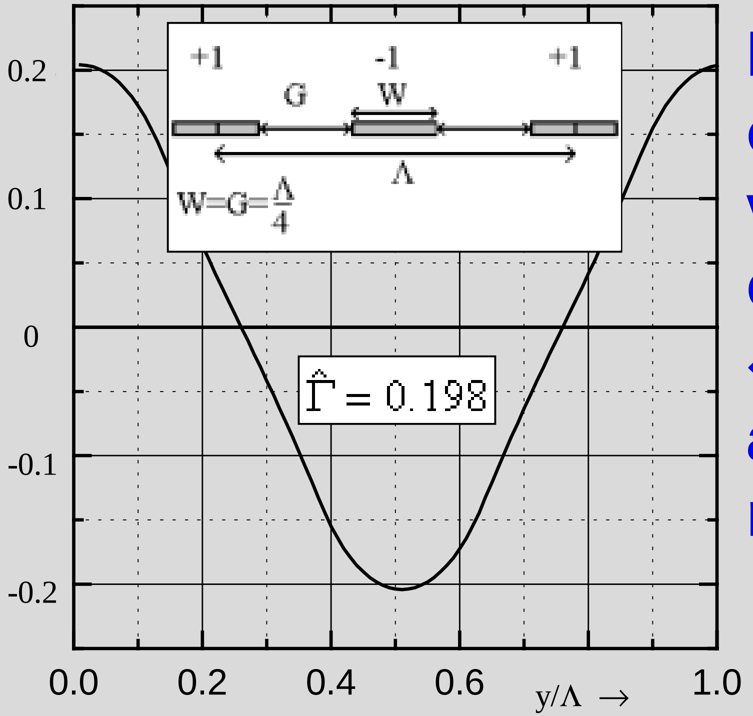
back-to-back



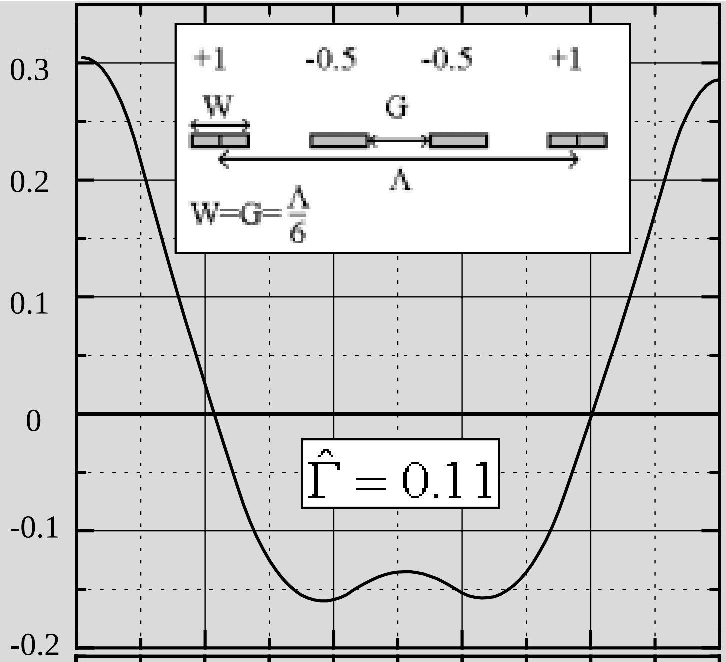
equalizer not working

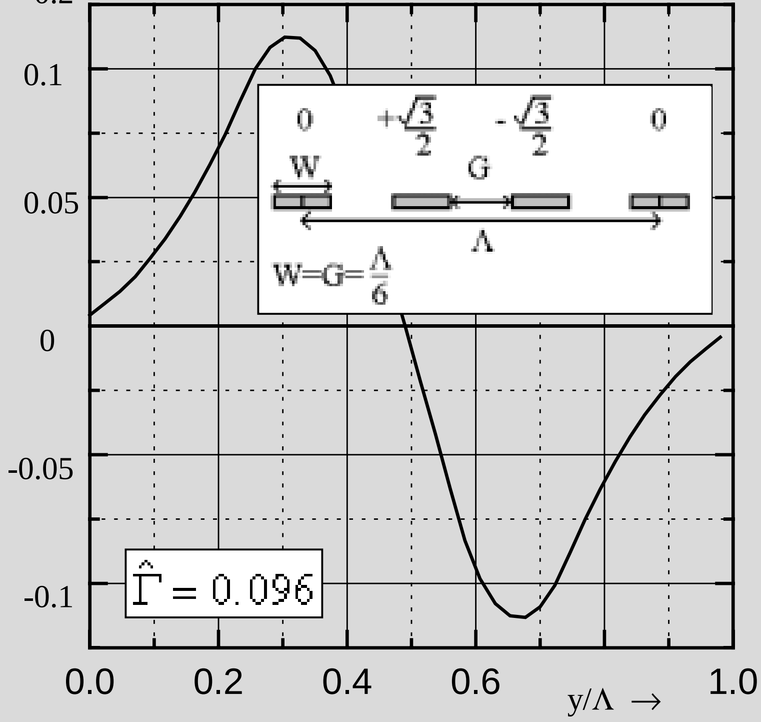


equalizer working



Local field overlap integral Γ vs. longitudinal coordinate *y* /Λ in ← 2-phase and 3-phase → mode converters





Effective Γ of 2-phase design is $\hat{\Gamma} = 0.086 \ldots 0.098$, as it needs at least twice the length of 3-phase design, which has a $\hat{\Gamma} = 0.096 \ldots 0.11$.

⇒ 3-phase performs equal to or slightly better than 2-phase design.

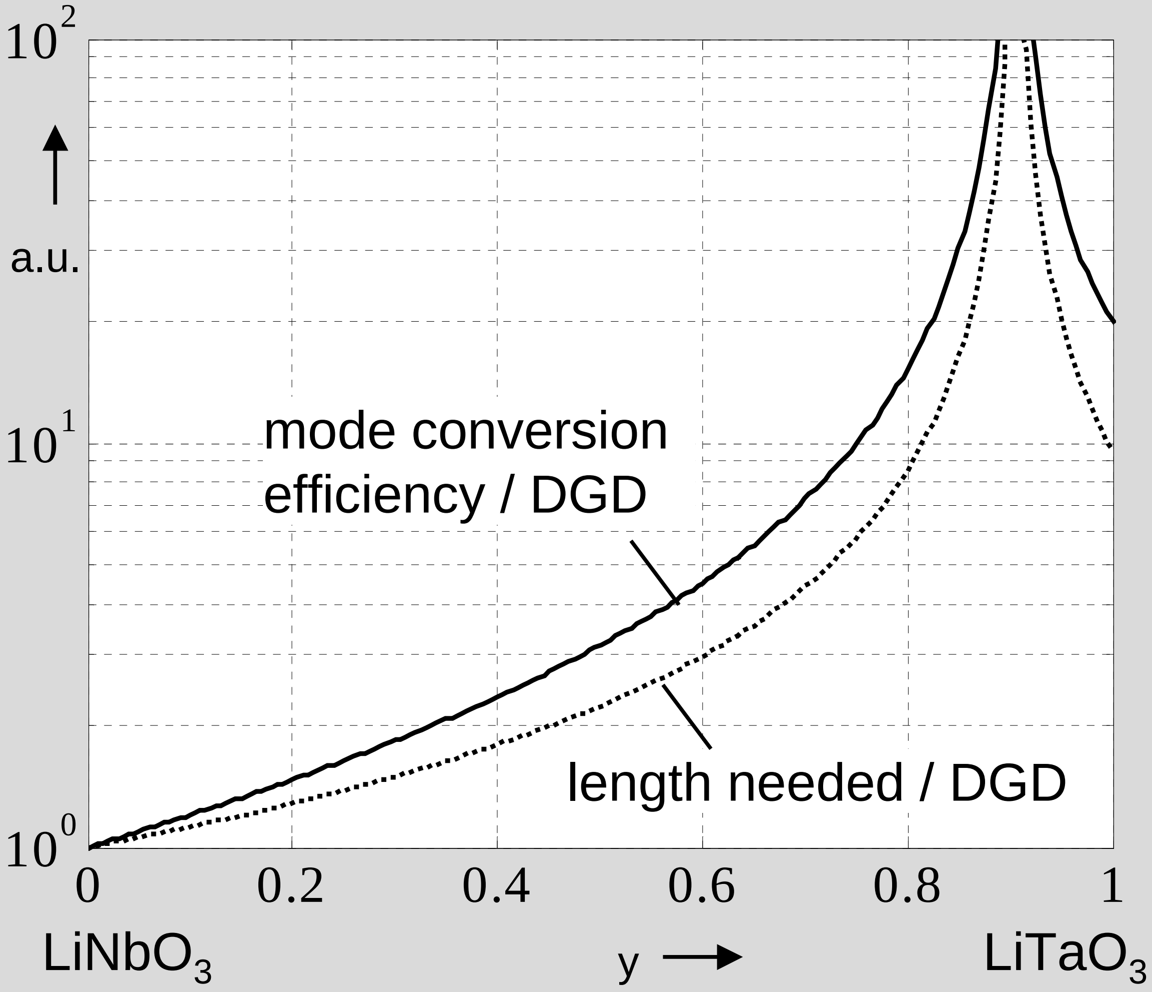
If maximum voltage rather than field strength is limited, 3-phase design performs 1.26...1.44 times better than 2-phase design.

Distributed PMD compensator for higher bit rates

- Exemplary task: Compensate for one bit duration of DGD.
- ~1.5...3.5 ps of DGD are needed for one mode conversion, depending on how good phase matching is.
- This should be sufficient for 80Gbit/s. 160Gbit/s would be difficult.
- To reach ≥160Gbit/s, DGD per length may be reduced. Possibilities:
  - Off-axis propagation. Is not practical because hybrid mode of non-buried waveguide will suffer increased loss.
  - Waveguides with proton exchange. Problem: PDL
  - $LiTaO_3$ and $LiNb_{1-y}Ta_yO_3$. Problems: Low Curie temperature requires repoling after Ti waveguide fabrication. $LiNb_{1-y}Ta_yO_3$ is not available today.

Discussions with W. Sohler, K. Betzler, S. Bhandare and K. Buse are acknowledged.

Distributed X-cut, Y-prop. PMD compensator in $LiNb_{1-y}Ta_yO_3$



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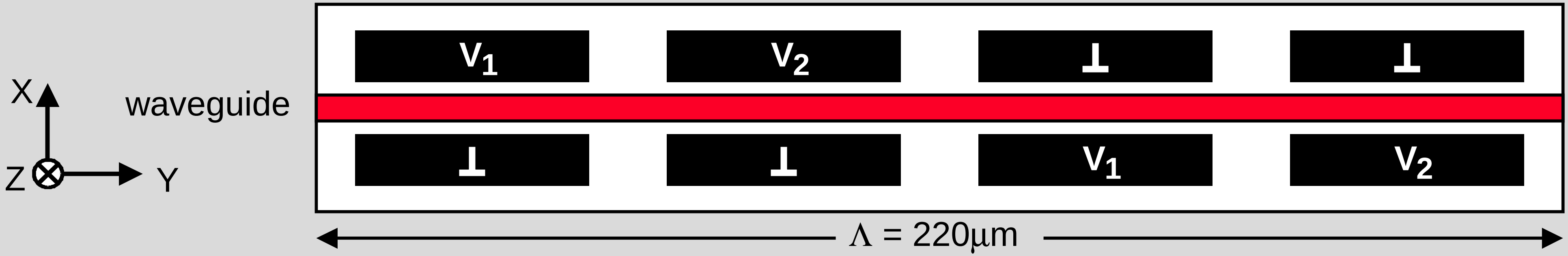
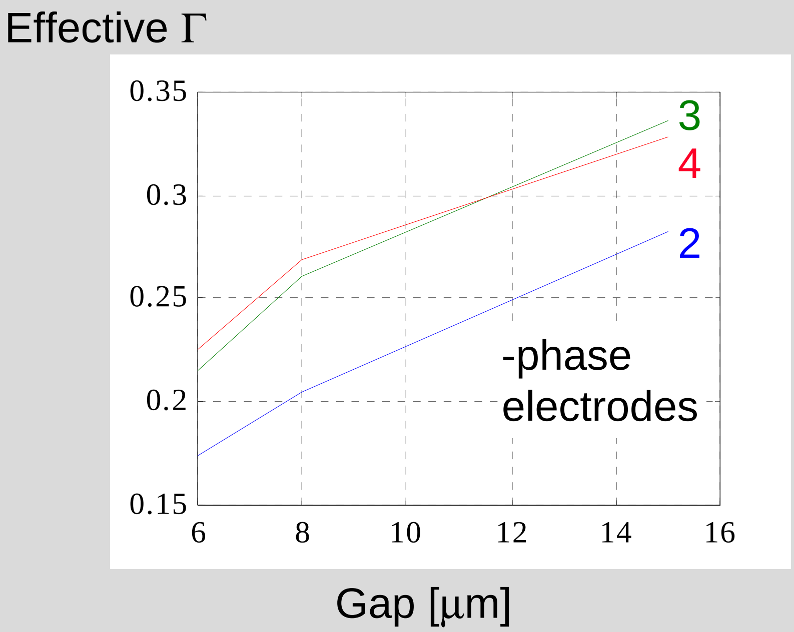
- $LiTaO_3$ can increase efficiency per DGD by a factor of ~20 while DGD per length is ~10 times smaller than for $LiNbO_3$. Should work up to at least 640Gbit/s.
- $LiNb_{1-y}Ta_yO_3$:
  - Lower device length than for $LiTaO_3$ at 160...320Gbit/s
  - Sign reversal of Δn promises Tbit/s PMD compensation near $y = 0.9$.
- Problem of X-cut, Y-prop. in devices with low birefringence: large electrode gaps, very high voltages (10 V/µm)!
  Solution: Z-cut.

Distributed Z-cut PMD compensator in $LiTaO_3$



- Field across waveguide is decisive for mode conversion.
- Multiphase electrodes are most efficient.
- Example: 4-phase electrodes, need only 2 independent voltages.
- Shown is one period.
- Several periods form one in-phase and quadrature mode converter.
- Several mode converters form a distributed PMD compensator.
- Compensation capability for at least 640Gbit/s



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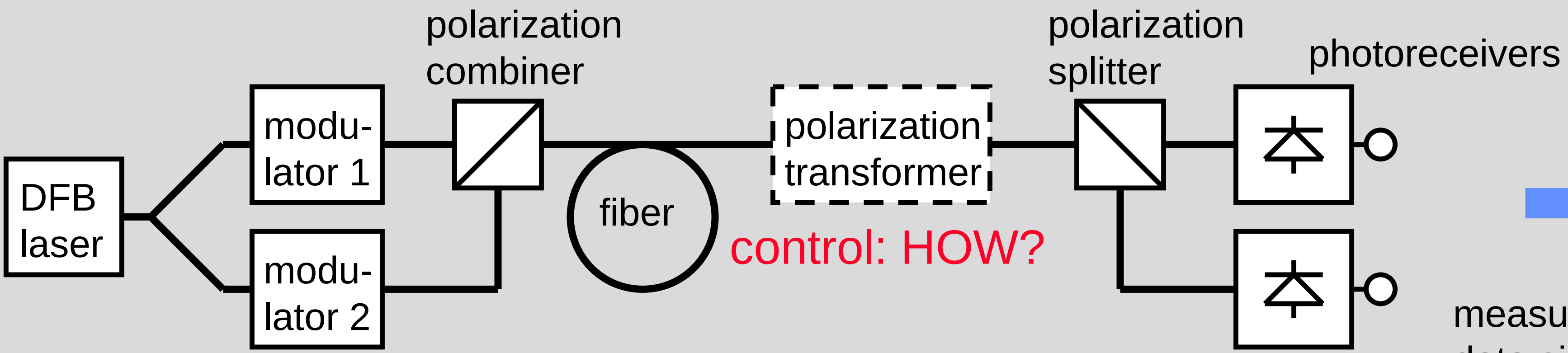
Overview

- Introduction
- Electrical PMD compensation
- PMD detection
  - 1st-order PMD detection
  - Higher-order PMD detection
  - Polarization scrambling
- Optical PMD compensation
- Polarization division multiplex
- Conclusions

Motivation for polarization division multiplex transmission

- Doubled fiber capacity
- 2×40Gbit/s NRZ polarization division multiplex tolerates more PMD than
  - 80Gbit/s NRZ single-channel transmission, and
  - much more than polarization-interleaved 40Gbit/s NRZ single-channel transmission with halved frequency spacing and polarizer at RX.
- 2×40Gbit/s PolDM tolerates more chromatic dispersion than 80Gbit/s.
- Distributed PMD compensator is able to output any desired polarization state ⇒ Either polarization division multiplex or PMD compensation come at a fairly low incremental cost.

Polarization division multiplex (PolDM): Principle and effect of polarization crosstalk in receiver



$$\begin{aligned} i_1 &\propto b_1\cos^2\psi/2 + b_2\sin^2\psi/2 + \\ i_2 &\propto b_1\sin^2\psi/2 + b_2\cos^2\psi/2 - \end{aligned}\boxed{\begin{aligned} b_1 b_2\cos\varphi\sin\psi \\ b_1 b_2\cos\varphi\sin\psi \end{aligned}}$$

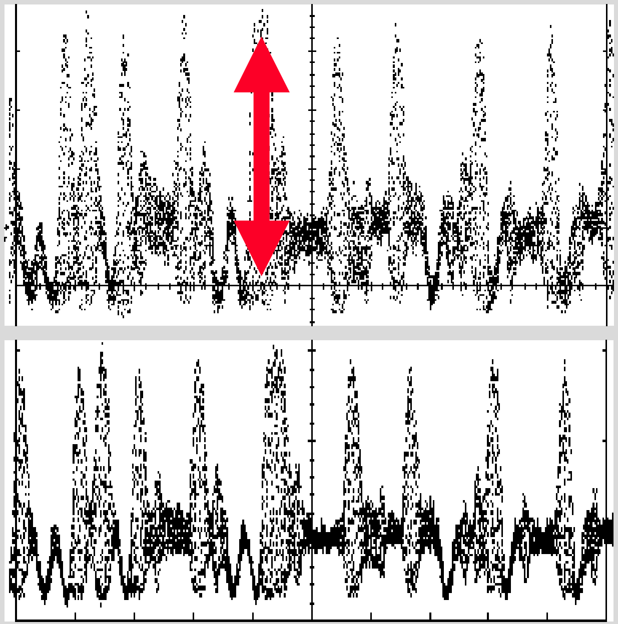
Photocurrents

Information bits

Polarization mismatch

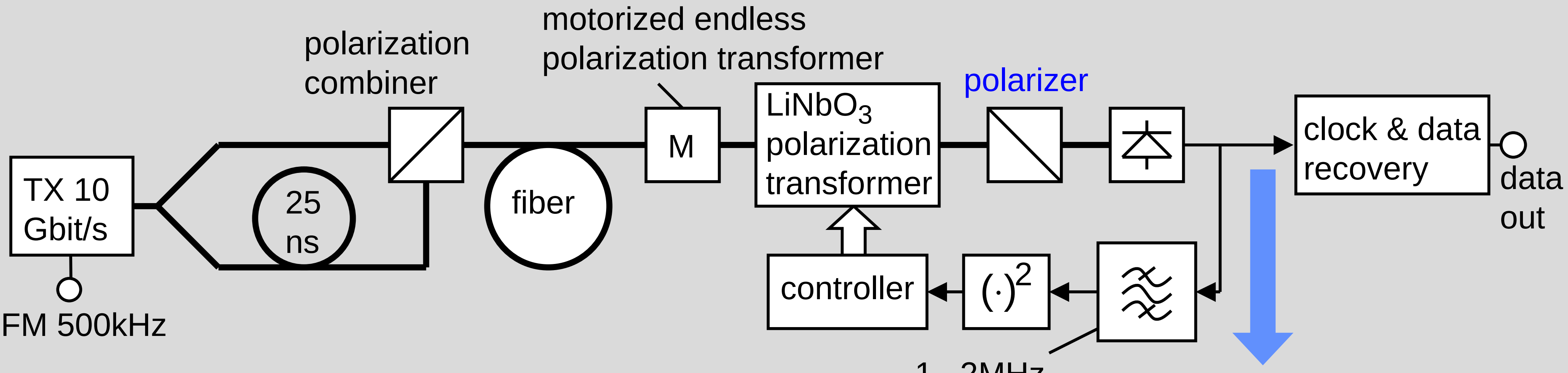
Interchannel phase difference

measured 2x10Gbit/s data signals without polarization control

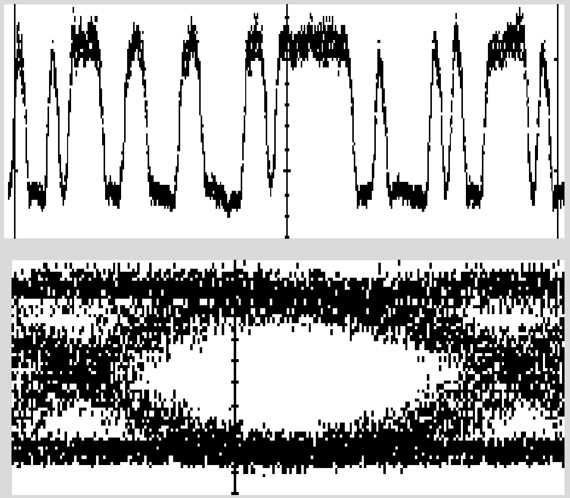


Interchannel interference causes penalty $\propto\psi$, not just $\propto\psi^2$, and should be used as an error signal.

Polarization division multiplex transmission using interference detection scheme



- FM and interchannel delay generate differential phase modulation to randomize interference.
- Extrapolated BER: 10^{-72}
- ~1ms signal acquisition time and up to 10 rad/s endless polarization tracking speed demonstrated.
- DSP can make control at least 10 times faster.

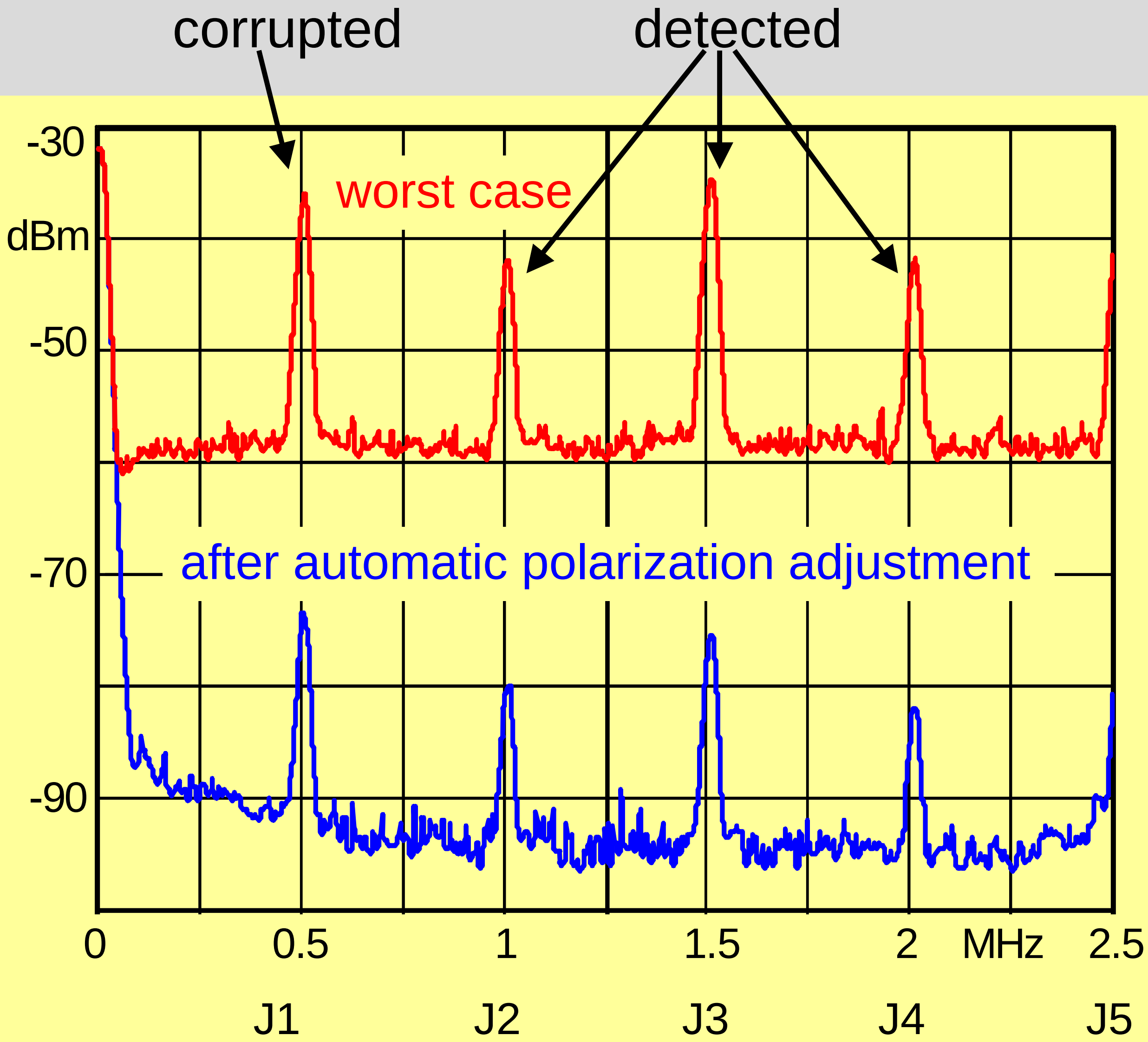


data output signal and its eye diagram

Interference causes Bessel spectrum of photocurrent

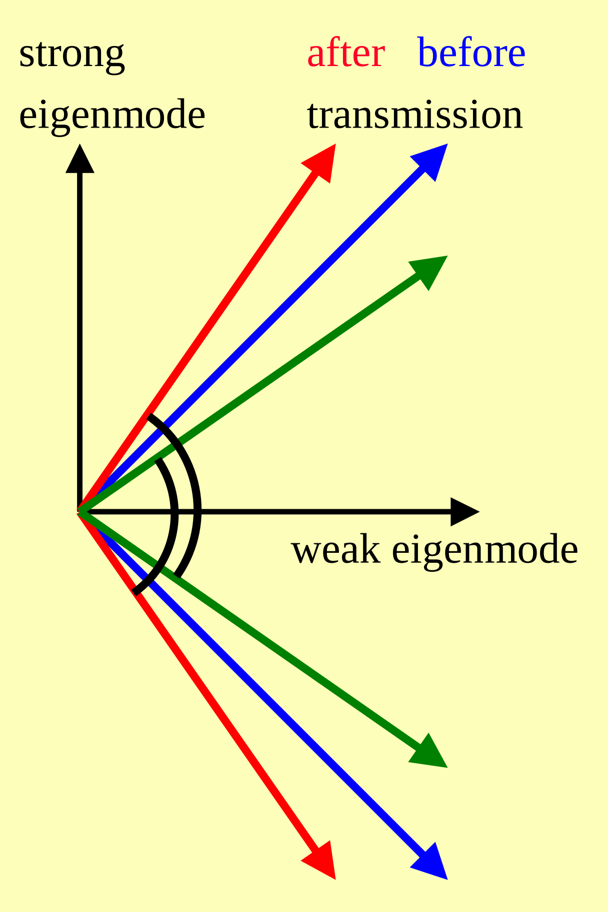
- Even vs. odd Bessel line powers fluctuate as a function of mean interchannel phase difference.
- Suitable power weighting makes signal independent of phase fluctuations and, to first order, of differential phase modulation index

$$\eta \sim \pi \underbrace{\Delta f_{\text{peak}-\text{peak}}}_{54\text{MHz}} \underbrace{\tau}_{25\text{ns}} = 4.2\ .$$



Polarization-dependent loss and gain

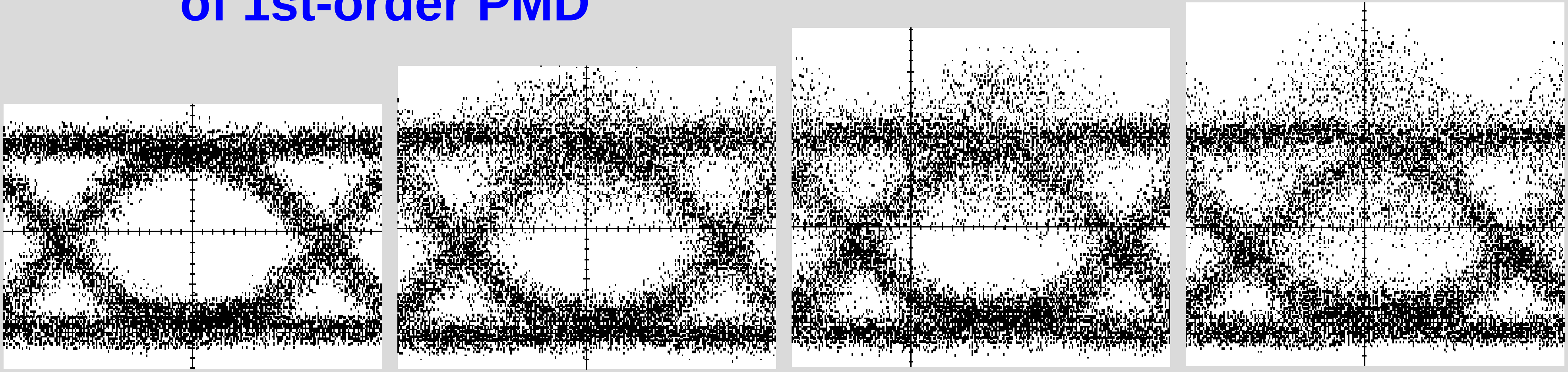
- Unequal magnitudes of Jones matrix eigenvalues
- Loss of polarization orthogonality is possible in the case of mixed eigenmodes.
- Analyze polarization state that is orthogonal to unwanted channel (but not necessarily identical to the wanted channel).



see L.J. Cimini et al., Preservation of polarization orthogonality through a linear optical system, Electronics Letters 23(1987), pp. 1365–1366

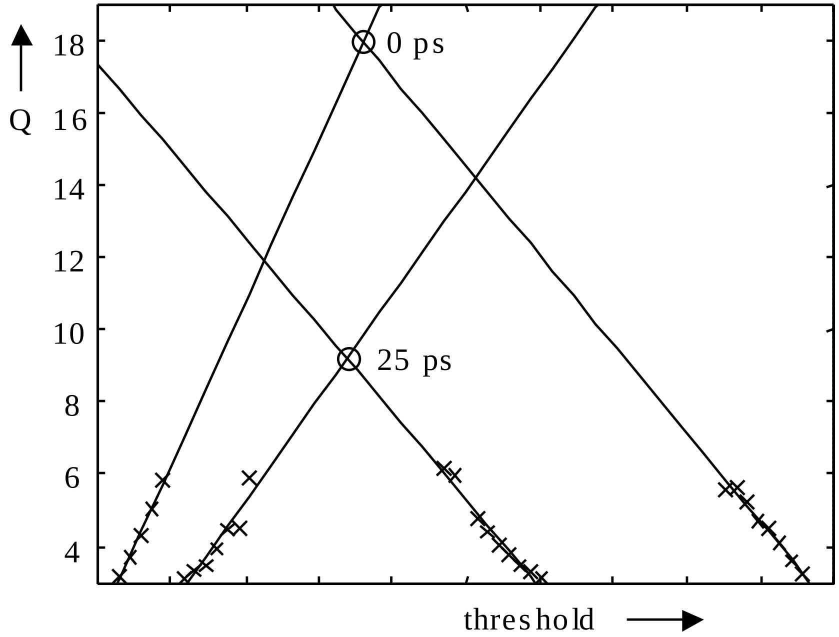
NRZ eye patterns in the presence of 1st-order PMD

Data rate: 10Gbit/s

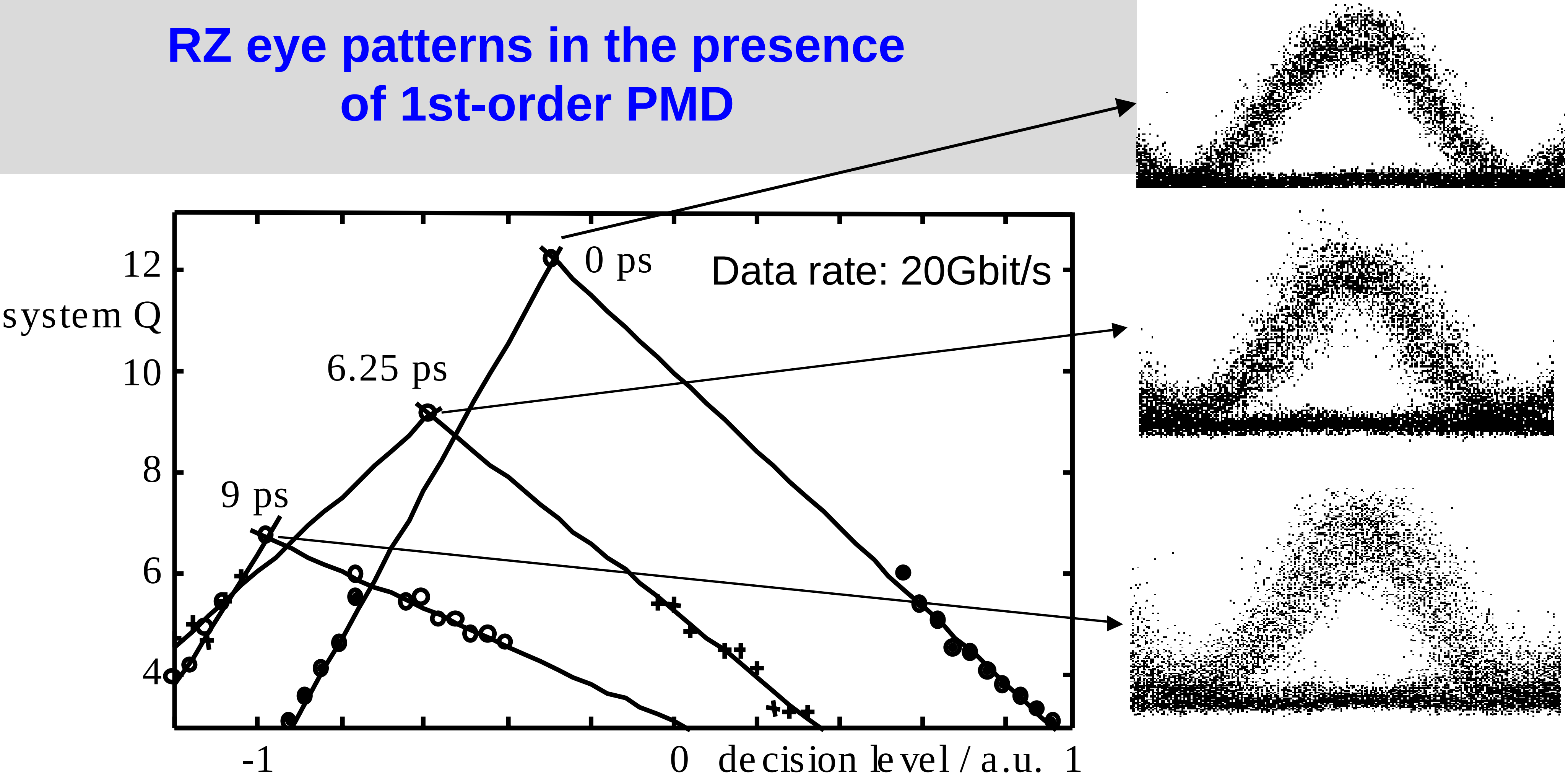


DGD = 0 *T* 0.19 *T* 0.25 *T* 0.35 *T*

- Worst case input polarization of PMF
- Polarization channels had ~0.4*T* mutual delay. ⇒ PMD crosstalk occurred roughly in the middle of the bits.
- With zero interchannel delay PMD crosstalk will occur between bits. ⇒ Best case!



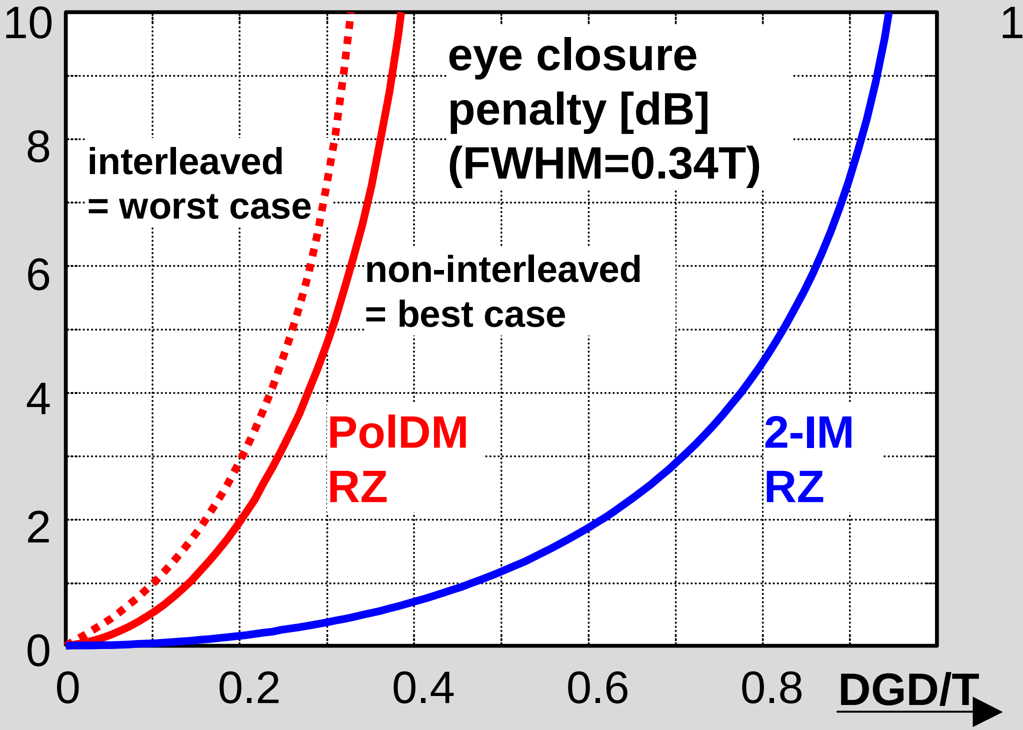
RZ eye patterns in the presence of 1st-order PMD

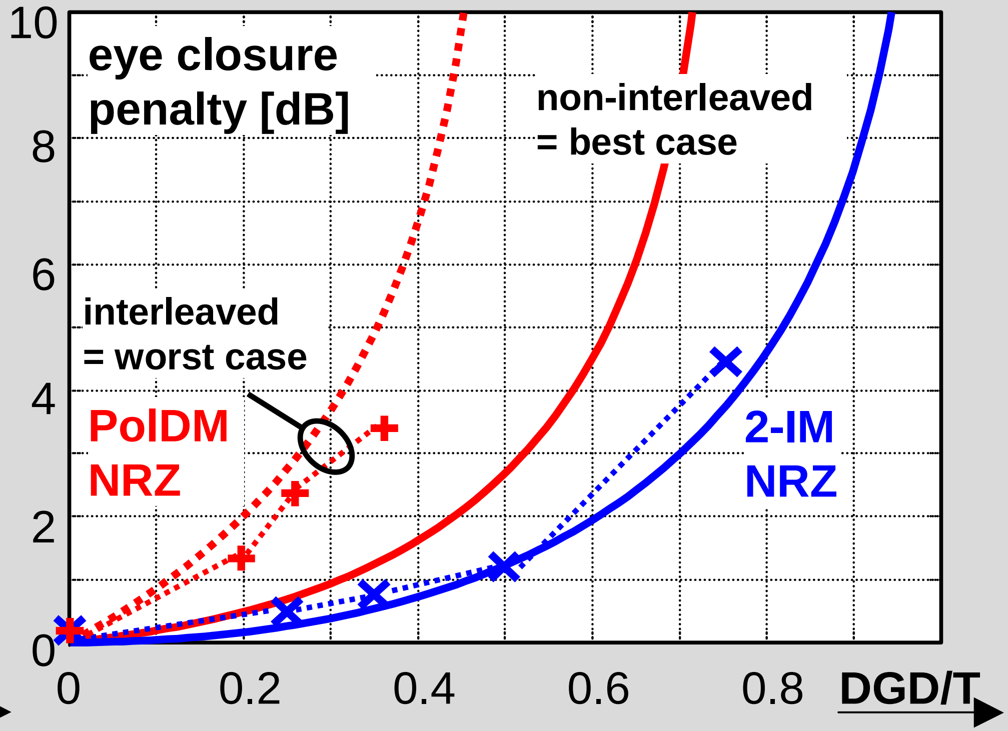


- worst-case alignment of PMD element
- DGD×bitrate product of ~0.125 is tolerated for RZ, as opposed to ~0.25 for NRZ.

PMD tolerance of polarization division multiplex vs. 2-IM

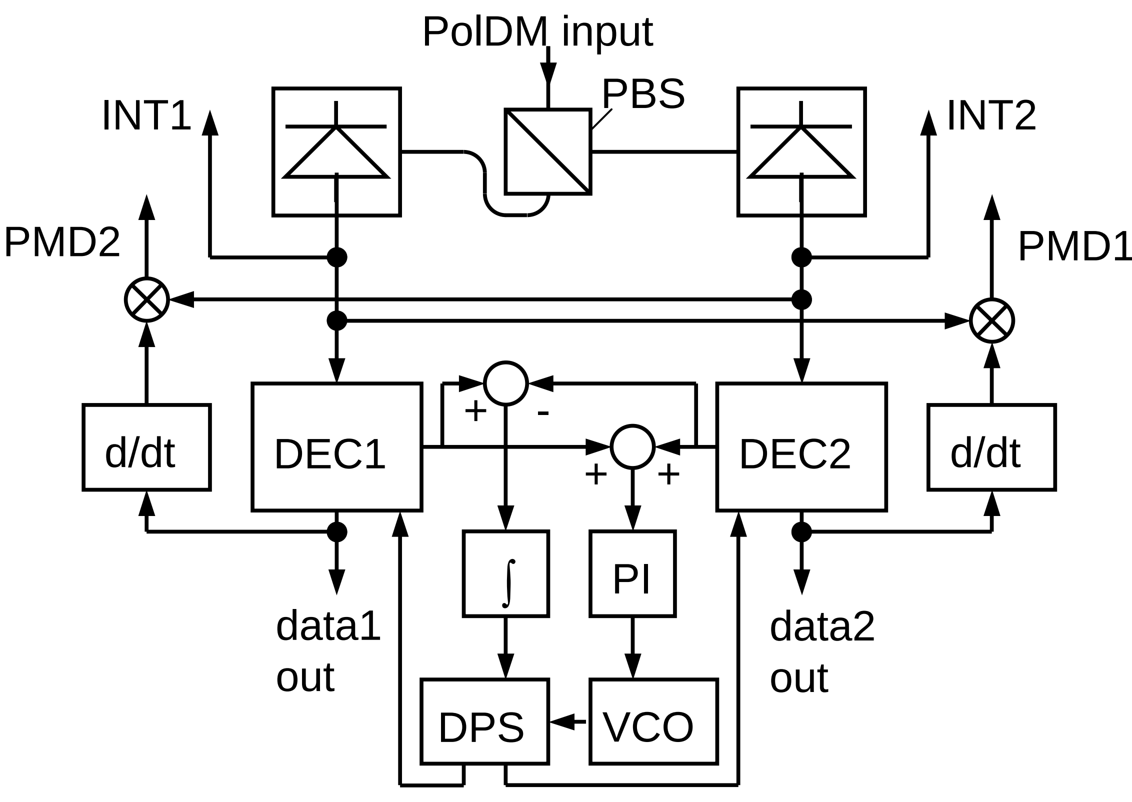
- Non-interleaved NRZ PolDM supports same capacity × fiber length product.
- RZ and phase-shaped PolDM transmission reduce PMD tolerance.
- Note: System penalty [dB] ≈ ≥2 × eye closure penalty [dB]





1st-order PMD detection for NRZ polarization division multiplex

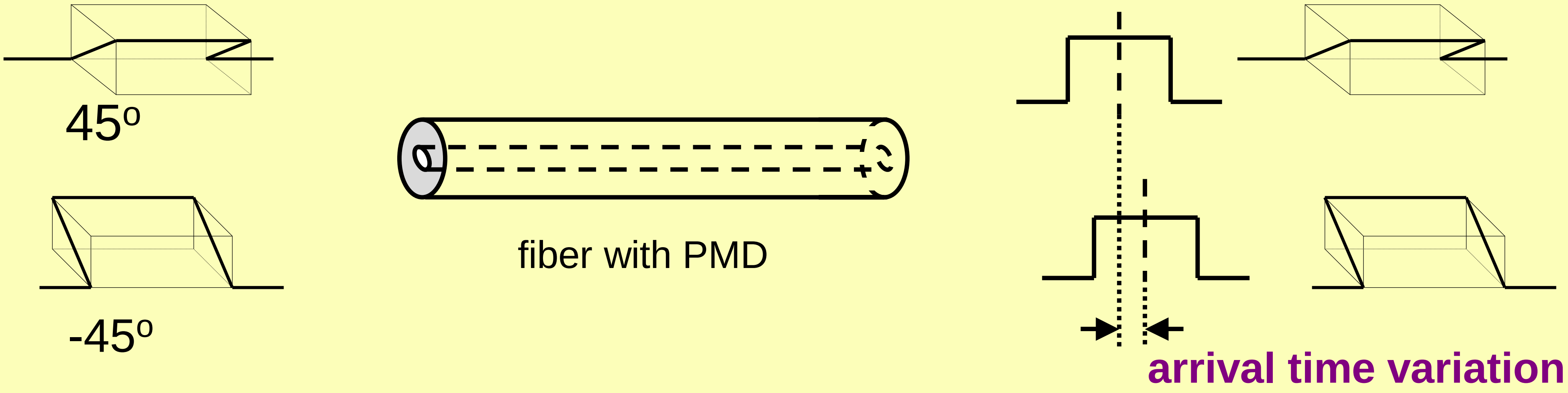
- PMD crosstalk occurs when unwanted polarization channel changes its sign.
- Polarity depends on sign change polarity and on cosine of interchannel phase difference.
- Multiplication of received signal *i* =1,2 with differentiated decision circuit output signal yields error signal PMD*i* which can be processed like the interference signals INT*i.*
- Differential clock phase shifter DPS (or optical PMD compensator) can compensate for static interchannel phase difference.



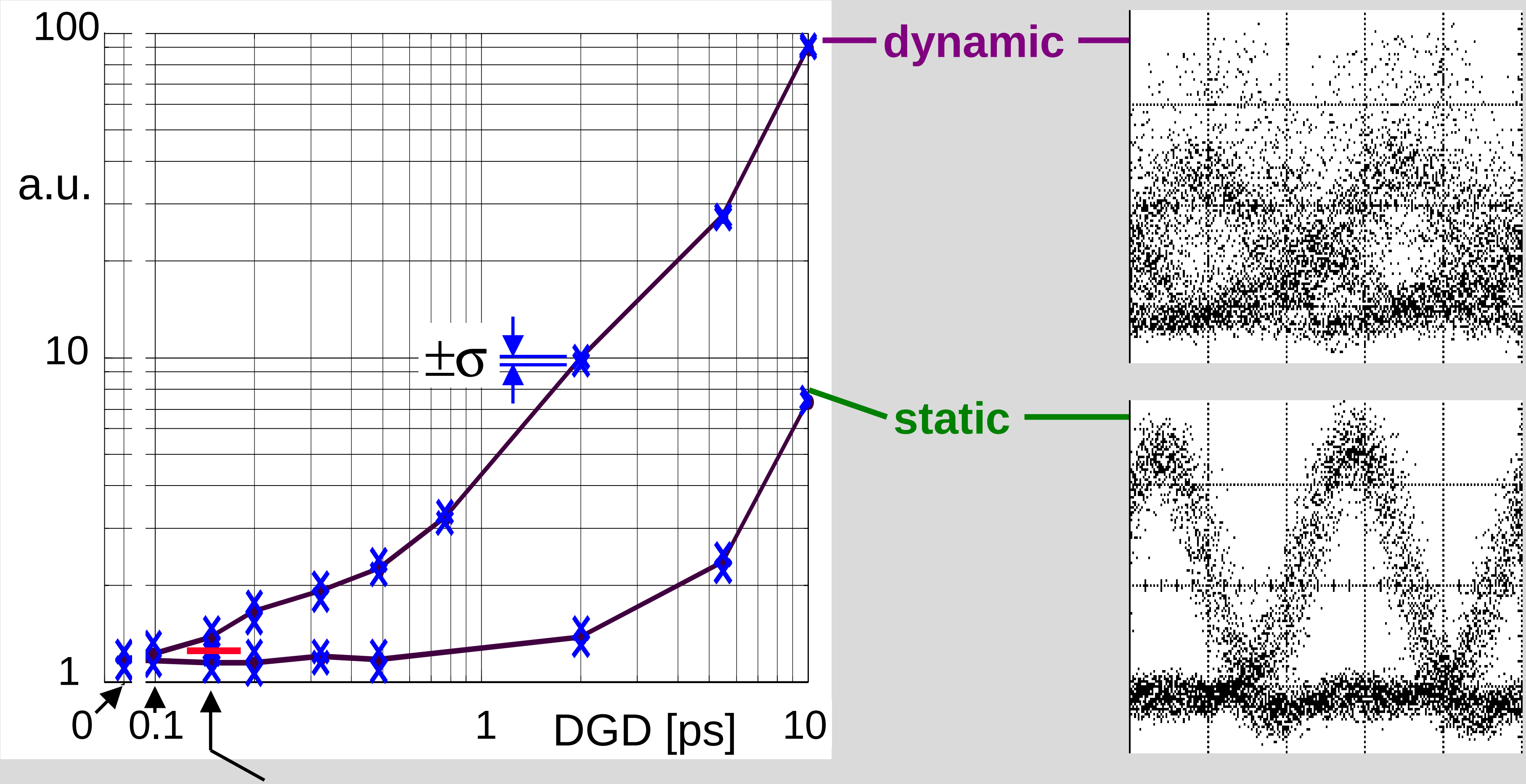
Arrival time variation for RZ polarization division multiplex transmission

- PMD with PSPs equal to 0°, 90° cause uncritical **static** arrival time difference between polarization channels.
- If single ones exite both principal states-of-polarization the arrival time of double ones depends **dynamically** on phase difference between the two polarizations:

PSPs: +45°, -45° retardation = $n \cdot 2\pi$

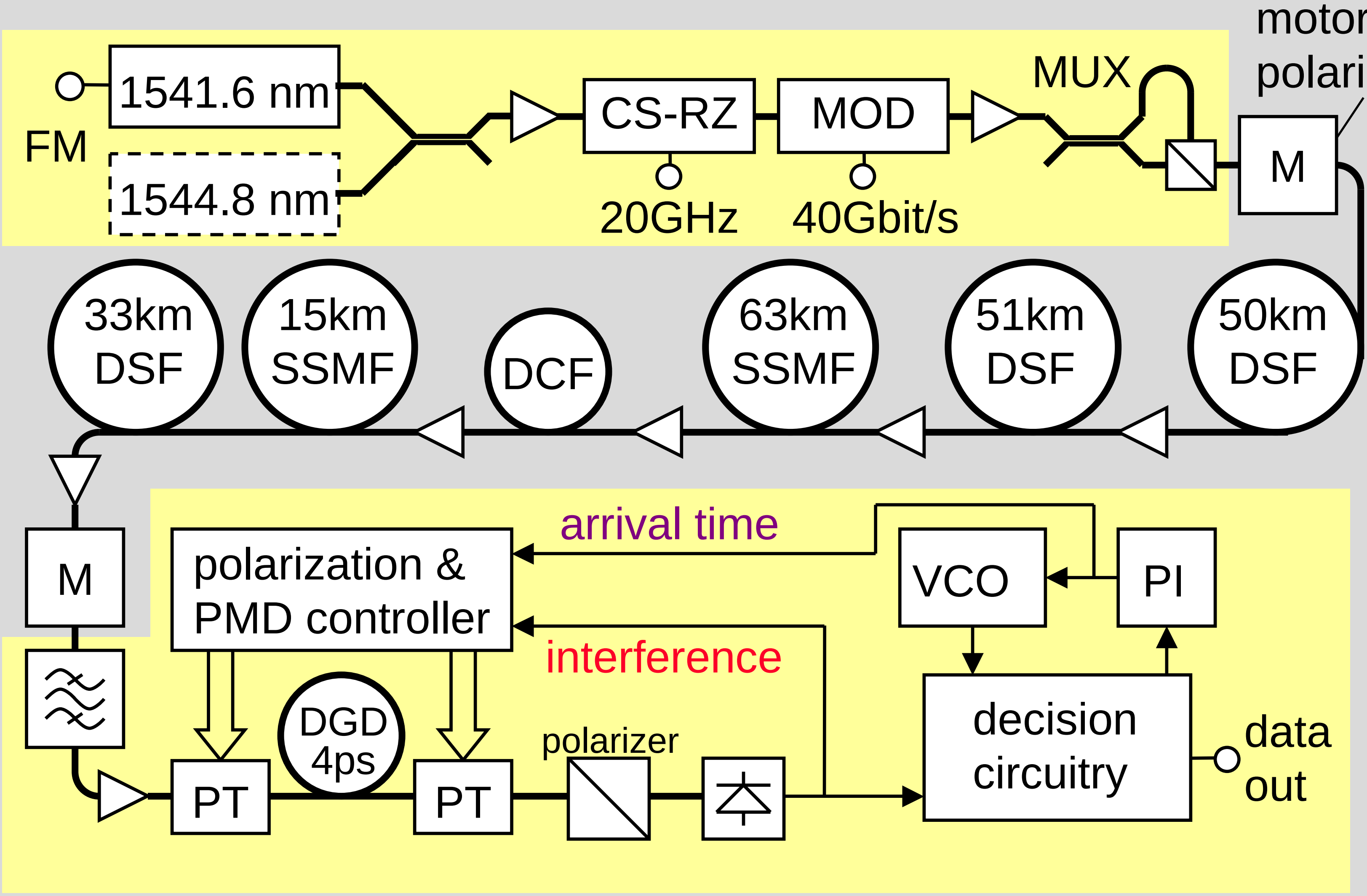


Root mean square arrival time variation vs. DGD at 40Gbit/s

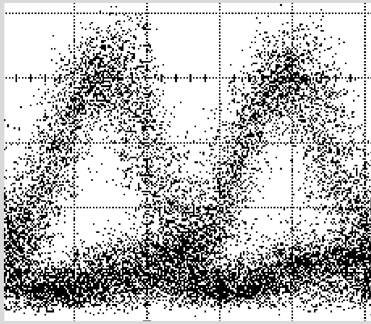


sensitivity 150fs, measured in 4.8µs

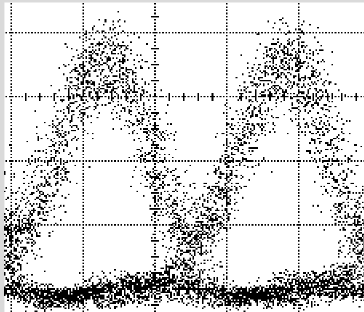
2×40Gbit/s, 212km polarization division multiplex transmission with endless polarization control and PMD compensation



ERRORS
without PMDC

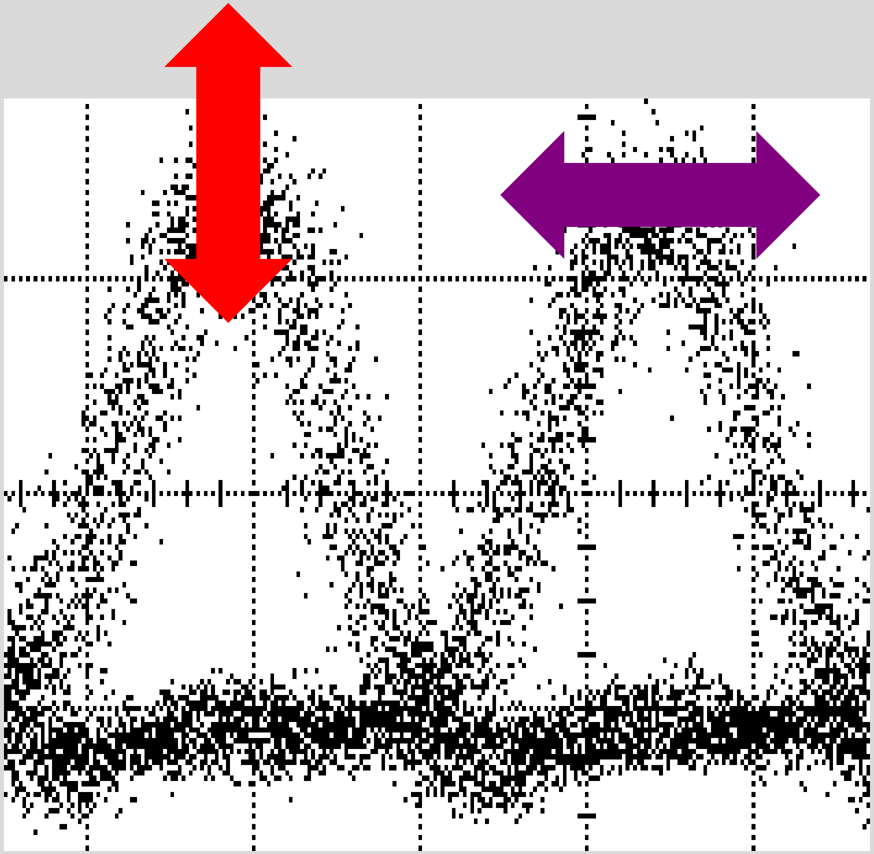


NO ERRORS
with PMDC



RZ polarization division multiplex signals in the presence of interchannel phase modulation

Polarization crosstalk
⇓
interference detection



PMD
⇓
arrival time detection

Conclusions (1): My „PMD compensation philosophy“

- Electrical compensation: Low-cost compromise.
- Electrical detection: Low-cost, high performance.
  - Arrival time detection, slope steepness difference, other methods ...
  - Polarization scrambler is needed or may be useful.
  - Optical detection is probably not required. If it is to be used, a shared polarization spectrometer is needed to bring cost down.
- Optical compensation: High performance.
  - At ≥40Gbit/s distributed PMD compensators offer a far better performance/cost ratio than discrete ones. X-cut, Y-propagation $LiNbO_3$ PMD compensators need to become commercially available.
  - For ≥160Gbit/s single-channel data rate distributed PMD compensators with lower Δn should be worked on, e.g., in Z-cut $LiTaO_3$.

Conclusions (2): Polarization division multiplex

- Electrical detection
  - Interference detection
  - Arrival time detection of PMD for RZ
  - Electronic PMD crosstalk detection for NRZ
- Optical compensation
- Either polarization division multiplex or PMD compensation come at a fairly low incremental cost (assuming X-cut, Y-propagation $LiNbO_3$ PMD compensators).
- Is attractive whenever available amplified bandwidth is limited.
- Even where amplified bandwidth is not limited it avoids the increased chromatic dispersion sensitivity and (for NRZ only) the increased PMD sensitivity of doubled per-channel bit rates.
  - Long-haul submarine systems?
  - Ultra-high capacity systems?

Controllability of a distributed PMD compensator

- Measured signal acquisition time for distributed $LiNbO_3$ PMD compensator: 50ms
- Reduced measurement intervals: ~10fold improvement expected
- Reduced electrode number (less than 146): ~10fold improvement expected
- Increased accuracy of new PMD detection methods: ~2fold improvement expected
- 250µs signal acquisition time?

References (1)

General, Introduction, PMD detection, Optical PMD compensation, Polarization division multiplex

1. If additional viewgraphs are shown in this tutorial they will be made available at http://ont.upb.de/publikationen/ecoc2002_noe_tut_add.pdf
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