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

Reinhold Noé
University of Paderborn
Electrical Engineering and Information Technology
Optical Communication and High-Frequency Engineering
D-33095 Paderborn

Acknowledgements:
D. Sandel, V. Mirvoda, F. Wüst, S. Bhandare, S. Hinz,
H. Herrmann, H. Suche, W. Sohler,
Siemens ICN, Deutsche Forschungsgemeinschaft, www.work-gmbh.com

ECOC 2002, Kopenhagen, Denmark, T4
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:

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

Output field after transfer through medium with transfer function/matrix $J$:

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

Definition of intensity (normalized optical power, photocurrent):

$$I = |E|^2$$

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

Intensity transfer through medium:

$$I_{in} = 1 + a \cos \omega t = 1 + a \text{Re}(e^{j\omega t})$$

$$E_{out} \quad I_{out} = 1 + a \text{Re}(H_m(\omega) e^{j\omega t})$$

$$H_m(\omega) = (1/2)e^{+}_{in}\left( J^{+}(\omega_0)J(\omega_0 + \omega) + J^{+}(\omega_0 - \omega)J(\omega_0) \right)e_{in}$$
What is polarization mode dispersion (PMD)?

Unitary Jones matrix: 

\[ J(\omega_0 + \omega) = \begin{bmatrix} u_1^* & u_2^* \\ -u_2 & u_1 \end{bmatrix} \quad \left| u_1 \right|^2 + \left| u_2 \right|^2 = 1 \]

PMD vector \( \Omega := \Omega_n \tau = 2 \begin{bmatrix} A \\ \text{Re } B \\ \text{Im } B \end{bmatrix} \) 

- \( A = -j(u_1^{*'} + u_2 u_2^{*'}) \)
- \( B = j(u_2 u_1^{*'} - u_1 u_2^{*'}) \)

Principal state-of-polarization (PSP)  Differential group delay (DGD)

Modulation transfer function for \( \omega \to 0 \):

\[ H_m(\omega) \sim \cos \omega \tau/2 + j\Omega_n^T S_{in} \sin \omega \tau/2 \]

\[ S_{in} = \pm \Omega_n \quad \Rightarrow \quad H_m(\omega) \sim e^{\pm j\omega \tau/2} \]

- 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**

Eye diagrams (DGD = 3T/8):
- Fast PSP
- Both PSPs excited with equal powers = worst case

Fiber is birefringent due to unwanted core ellipticity!

Eye closure \( \propto \tau^2 \Rightarrow \) difficult to detect for small \( \tau \)
Small-signal modulation transfer function of two DGD sections

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

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

Approximations for \(|\omega \tau_i| \ll 1\) yield geometrical interpretation using PMD vector direction/length and PMD profile area:

\[ \mathbf{s}_{in} = \pm \tilde{\Omega}_{n,\text{total}}^T \Rightarrow \]
\[ |H_m(\omega)|^2 \approx 1 - \left( \frac{(\omega/2)}{2} \left| \tilde{\Omega}_1 \times \tilde{\Omega}_2 \right| \right)^2 \]
Overview

- Introduction
- Electrical PMD compensation
- PMD detection
  - 1st-order PMD detection
  - Higher-order PMD detection
  - Polarization scrambling
- Optical PMD compensation
- Polarization division multiplex
- Conclusions
Due to negative binomial or $\chi^2$ noise from optical amplifiers, system penalty is larger than subdiagram opening penalty.
Calculated sensitivity penalty vs. normalized DGD

Penalty [dB]

Degrees-of-freedom:
- 128
- 32
- 8

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 $\chi^2$.
  - Finite extinction and unavoidable patterning penalties generally mask the first $\sim 1$...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!
Overview

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

- 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 sufficient?
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
Good PMD detection requires finely spaced bandpass filters.

Ideally, the power spectral density should be made \( \propto \text{sinc}^2(\frac{\omega T}{2}) \cdot |H_{RX}(\omega)|^2 \), 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 \( \tau_1 + \tau_2 \).

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.
PMD detection in 40Gbit/s transmission system

- Clock recovery PLL in receiver tracks arrival time variations.
- Arrival time $\propto$ clock phase $\propto$ integral of VCO input signal
- Differential group delay (DGD) $\propto$ arrival time variations
- Bit rate scalability
  - "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.

![Diagram of PMD detection in 40Gbit/s transmission system](image)

- TX
- polarization scrambler
- fiber
- PMD
- decision circuitry
- VCO
- PI
- rms
- $\Delta \hat{t}_{rms}$
- $\Delta \hat{t}(t)$
- @ 770fs of DGD

- Bit rate scalability
  - "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

- DFB laser
- MOD
- polarization scrambler
- controller
- VCO
- PI
- decision circuitry
- data out
- LiNbO₃ polarization transformers
- motorized endless polarization transformer

Vertical broadening of ones is due to slow PDL.

- 33km DSF
- 13km SSMF
- DCF
- 63km SSMF
- 51km DSF
- 50km DSF
- M
- 40Gbit/s

1st-order PMD detection
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

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

\[ \Rightarrow 0.88 \text{ps or 1.35ps sensitivity} \]

2.4\mu s measurement interval (417kHz scrambling frequency)
1st-order PMD detection

3-Dimensional DOP-Evaluation
courtesy
Rosenfeldt et al., ECOC 2001

experimental setup at 40 Gbit/s RZ:

received SOPs form an ellipsoid:

DGD= 0 ps
DGD= 1.25 ps
DGD= 8 ps

DOP ≈ 1 ⇒ PSP
DOP = f(DGD)

long axis
short axis
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

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

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

** in principle

Arrival time detection is easily realized with commercially available technology.
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.

\[ \text{maximum} > 0 \]
\[ \text{slope} \]
\[ \text{steepness} \]
\[ \text{difference} \]
\[ \text{minimum} < 0 \]

\[ \frac{\text{d}}{\text{d}t} \]
Higher-order PMD detection

Effects of DGD loop on 40Gbit/s eye diagram

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

Measurement:

![Diagram showing curvature difference with positive maximum and negative minimum](image)

Input polarization parallel to linear motion of DGD profile endpoint.

Input polarization parallel to quadratic motion of DGD profile endpoint.
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

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

Slope steepness difference (+ highpass output power) measurement is attractive.
Electrooptic „tennis ball“ polarization scrambler: Measured output Stokes parameter trajectories and spectra

Circular input polarization

Eigenvalues of Stokes vector covariance matrix: \(1/3 \pm 0.0055\)
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
Polarization scrambling See also P3.05

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

DFB laser → scan of input polarization

polarimeter → scrambler

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

Polarization scrambling

See also P3.05
Overview

- Introduction
- Electrical PMD compensation
- PMD detection
  - 1st-order PMD detection
  - Higher-order PMD detection
  - Polarization scrambling
- Optical PMD compensation
- Polarization division multiplex
- Conclusions
Differential group delay profiles are determined by inverse scattering. – Task of ideal PMD optical compensation.

PMD vector of two cascaded DGD sections: \[ \Omega = \Omega_{c,1} + R_1^{-1}\Omega_{c,2} \]

PMD vector of many cascaded DGD sections: \[ \Omega = \sum_{i=1}^{n} \left( \prod_{j=1}^{i-1} R_j^{-1} \right) \Omega_{c,i} \]

DGD profile: concatenated summands of overall PMD vector \( \Omega \)

Inverse scattering theory proposed by L. Möller

Same as for a fiber plus a perfect PMD compensator, which returns on fiber DGD profile until origin!
Principle of in-phase and quadrature mode converter in X-cut, Y-propagation LiNbO$_3$

Jones matrix of a waveguide section

\[
\begin{bmatrix}
\cos \frac{\phi}{2} & e^{-j \pi(\kappa_1 + j\kappa_2)} \sin \frac{\phi}{2} \\
je^{j \pi(\kappa_1 + j\kappa_2)} \sin \frac{\phi}{2} & \cos \frac{\phi}{2}
\end{bmatrix}
\]

with retardation \( \phi = 2m \sqrt{\kappa_1^2 + \kappa_2^2} \)

in phase: \( \kappa_1 \) linear mode coupling with \( \pm 45^\circ \)

quadrature: \( \kappa_2 \) 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 !
Distributed PMD compensator in X-cut, Y-propagation LiNbO₃

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

Fabricated by Prof. Sohler, Univ. Paderborn
Experiment performed with Siemens ICN

20Gbit/s PMD compensation with distributed PMD compensator

- TX 20 Gbit/s
- M
- DGD 10ps
- M
- DGD 20ps
- PMD compensator, 43ps
- Motorized endless polarization transformers
- Photodiode
- Clock & Data Recovery
- Controller

- log(BER)
- Power @ 10GHz
- Power @ 5GHz
- Time [min]
- Back-to-back
- Compensator alone
- 30 ps compensated
- 30 ps, compensator off
40 Gbit/s eye diagrams with 
LiNbO\textsubscript{3} distributed PMD compensator

back-to-back

equalizer not working

equalizer working
Effective $\Gamma$ 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 $\hat{\Gamma} = 0.096 \ldots 0.11$.

$\Rightarrow$ 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 $\geq$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$_y$O$_3$. Problems: Low Curie temperature requires repoling after Ti waveguide fabrication. LiNb$_{1-y}$Ta$_y$O$_3$ 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$_y$O$_3$

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$_y$O$_3$:
- Lower device length than for LiTaO$_3$ at 160...320Gbit/s
- Sign reversal of $\Delta n$ 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.

S. Bhandare, R. Noé, 2002
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 640 Gbit/s

S. Bhandare, R. Noé, 2002
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

\[ i_1 \propto b_1 \cos^2 \psi/2 + b_2 \sin^2 \psi/2 + b_1 b_2 \cos \phi \sin \psi \]
\[ i_2 \propto b_1 \sin^2 \psi/2 + b_2 \cos^2 \psi/2 - b_1 b_2 \cos \phi \sin \psi \]

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

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 $\eta \sim \pi \frac{f_{\text{peak-peak}}}{\Delta f_{\text{peak-peak}}} \tau = 4.2$.

54MHz 25ns
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

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

Data rate: 10Gbit/s
RZ eye patterns in the presence of 1st-order PMD

Data rate: 20Gbit/s

- worst-case alignment of PMD element
- DGD×bitrate product of ~0.125 is tolerated for RZ, as opposed to ~0.25 for NRZ.
Non-interleaved NRZ PolDM supports same capacity × fiber length product.

RZ and phase-shaped PolDM transmission reduce PMD tolerance.

Note: System penalty [dB] \( \approx \geq 2 \times \) 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 exit both principal states-of-polarization the arrival time of double ones depends **dynamically** on phase difference between the two polarizations:

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

![Diagram](attachment:image.png)
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

- 1541.6 nm (FM)
- 1544.8 nm
- 20GHz
- 40Gbit/s
- 50km DSF
- 63km SSMF
- 51km DSF
- 50km DSF
- 33km DSF
- 15km SSMF
- DCF
- MUX
- M
- PMD controller
- VCO
- PI
- decision circuitry
- data out
- motorized endless polarization transformer
- ERRORS without PMDC
- NO ERRORS with PMDC

- CS-RZ
- MOD
- PT
- DGD 4ps
- polarizer
- arrival time
- interference
RZ polarization division multiplex signals in the presence of interchannel phase modulation

Polarization crosstalk \(\downarrow\) interference detection

PMD \(\downarrow\) 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.
  - At $\geq 40\text{Gbit/s}$ 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 $\geq 160\text{Gbit/s}$ single-channel data rate distributed PMD compensators with lower $\Delta n$ 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 LiNbO₃ 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
2. Extensive bibliographies can be found at http://ont.upb.de/polarization_bibliography.htm and http://www.om.tu-harburg.de/Forschung/Pmd/PmdBibliography.htm
7. D.A. Smith, R. Noé, New polarization scrambler using Ti:LiNbO₃ rotating waveplate, Proc. IGWO 1988, pp. 111-114, OSA, Santa Fe, NM, USA.
References (2)


References (3)

41. T. Ito et al., “6.4 Tb/s (160 x 40 Gb/s) WDM transmission experiment with 0.8 bit/s/Hz spectral efficiency”, European Conference on Optical Communication 2000, Munich, Germany, post-deadline paper 1.1, Sept 3 – 7 2000

47. Chongjin Xie, Magnus Karlsson, Henrik Sunnerud, Peter A. Andrekson, Comparison of soliton robustness with respect to polarization-mode dispersion with first-order polarization-mode dispersion-compensated linear systems, Optics Letters 26(10), pp. 672-674 (2001)


References (5)


Electrical PMD compensation

70. D. Schlump, B. Wedding, H. Bülow: "Electronic equalization of PMD and chromatic dispersion induced distortion after 100 km standard fiber at 10 Gbit/s", ECOC ’98, Madrid, Spain, WdC14


References (6)


