In-service PMD monitoring and compensation

Reinhold Noé, David Sandel

University of
Paderborn

Electrical Engineering and Information Technology
Optical Communication and High-Frequency Engineering
D-33095 Paderborn


Most of this material can also be found in R. Noé et al., „PMD in High-Bit-Rate Transmission and Means for Its Mitigation“, IEEE JSTQE 10(2004)2, pp. 341-355, and its references.
Overview

- Introduction
- Electrical PMD compensation
- PMD detection
  - 1st-order PMD detection
  - Higher-order PMD detection
  - Polarization scrambling
- Optical PMD compensation
- Polarization division multiplex
- Limits due to fiber nonlinearity
- Coherent optical systems
- Higher-order PMD description
- Conclusions
Small-signal intensity modulation transfer function of a linear lossless optical medium

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

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

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

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

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:

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

$$E_{out}$$

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

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

Unitary Jones matrix:

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

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

\[ A = -j(u_1 u_1^* + u_2 u_2^*) \]
\[ B = j(u_2 u_1^* - u_1 u_2) \]

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

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

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

\[ S_{in} = \pm \Omega_n \]

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

- PMD effect scales with bit rate.
- 1st derivative of output polarization with respect to optical frequency vanishes for PSPs (Poole/Wagner, 1986)!
Eye diagrams (DGD = 3T/8):

- Fast PSP
- Both PSPs excited with equal powers = worst case

**Pure 1st-order PMD**

Fiber is birefringent due to unwanted core ellipticity!

Eye closure $\propto \tau^2 \Rightarrow$ difficult to detect for small $\tau$
Electrical PMD compensation by quantized feedback

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. Noé, 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 ~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!
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
PMD detection for DPSK signals using an electrical highpass filter

For small DGDs, highpass output power drops with the square of the DGD.
- Small DGDs are difficult to detect.
- Ambiguous readout
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)

- 0ps
- 2ps
- 5.5ps
- 19ps
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.

```
1st-order PMD detection
```
40Gbit/s PMD compensation with arrival time detection

- DFB laser
- MOD
- polarization scrambler
- M
- motorized endless polarization transformer
- 33km DSF
- 13km SSMF
- DCF
- 63km SSMF
- 51km DSF
- 50km DSF
- LiNbO₃ polarization transformers
- controller
- PT
- DGD 6ps
- VCO
- PI
- decision circuitry
- data out

Vertical broadening of ones is due to slow PDL.
Prescaled clock spectra in the presence of a 19 ps DGD

without PMD compensation

with 10 ps + 8.5 ps PMD compensator

10 min persistence, rotating emulator

~30 dB
Root mean square arrival time variation vs. differential group delay for „tennis ball“ polarization scrambler

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

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

2.4 μs measurement interval (417kHz scrambling frequency)
Chromatic dispersion detection at 40Gbit/s using synchronous arrival time detection

- Small pump current modulation of TX laser at 5MHz
- If there is chromatic dispersion (CD), FM modulates arrival time, detectable in RX at VCO input.
- Parasitic AM provides reference for synchronous (lock-in) detection of arrival time modulation.

Operable over more than „one eye closure“
- 100 attoseconds or 50 fs/nm accuracy
- 2 ps/nm longterm drift
1st-order PMD detection

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:

- 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.

photodiode

\[ \frac{d}{dt} \]

maximum > 0

slope steepness difference

minimum < 0
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:

\[ \frac{d}{dt} \text{ maximum} > 0 \]
\[ \text{curvature difference} \]
\[ \frac{d}{dt} \text{ minimum} < 0 \]
40Gbit/s transmission experiment with PMD compensation

40Gbit/s transmission experiment with PMD compensation

Higher-order PMD detection
Results

DGD sections | Loop area
---|---
0+0+0+0ps, no PDL | 0 ps²
0+0+0+0ps, with PDL | 0 ps²
2.2+4+4+2.2ps | 8.8 ps²
6.25+4+4+6.25ps | 25 ps²
6.25+6.25+6.25+6.25ps | 39 ps²
6.25+19+22.8+6.25ps | 261 ps²
Typical eye patterns for various polarizations at the input of a DGD profile loop, with stopped polarization scrambler

back-to-back

6.25+6.25+6.25+6.25ps
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>strong</td>
<td></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>decreases readout</td>
<td></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
  \[
  S = \begin{bmatrix}
  \left(1 + \frac{1}{\sqrt{3}}\right) / 2 \cdot \cos \omega t - \left(1 - \frac{1}{\sqrt{3}}\right) / 2 \cdot \cos 3\omega t \\
  \left(1 + \frac{1}{\sqrt{3}}\right) / 2 \cdot \sin \omega t + \left(1 - \frac{1}{\sqrt{3}}\right) / 2 \cdot \sin 3\omega t \\
  \sqrt{2/3} \cdot \cos 2\omega t
  \end{bmatrix}
  \]

- Eigenvalues of Stokes vector covariance matrix: \(1/3 \pm 0.0055\)

- Only 3 harmonics!
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

Histogram for 51 equispaced input polarizations

- Smallest eigenvalue
- Largest eigenvalue

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
Measured differential group delay profiles and ideal PMD compensation

PMD vector of two cascaded DGD sections:

\[ \tilde{\Omega} = \Omega_{1} + R_{1}^{-1}\Omega_{2} \]

Can be generalized by induction.

DGD profile: concatenated local backtransformed PMD vectors

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
Electrooptic waveplate, usable for endless polarization control

Noé et al., 1987/1988

- X-cut, Z-propagation LiNbO₃
- V₁ alone: horizontal/vertical birefringence
- V₂ alone: 45°/−45° linear birefringence
- Both effects combined:
  - Waveplate with adjustable retardation and orientation
  - Eigenmodes in S₁-S₂ plane
- Uninterrupted, „endless“ transformation of circular polarization into any state or vice versa.

For circular input polarization the output polarization is obtained by an azimuthal equidistant projection onto Poincaré sphere:

- Plane of normalized voltages:
In-phase and quadrature, periodic mode conversion in birefringent waveguide for endless polarization control: Soleil-Babinet analog (SBA)

Differential group delay ~0.26 ps/mm
Spatially periodic, X-directed (vertical) electric field perturbs local eigenmodes.

Example: Horizontal input polarization  $E_x = 1$, $E_y = 0$,  $S = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$

Mode conversion:

- In phase
  - $S_2 = 2 \text{Re}(E_x E_y^*) \neq 0$

- Quadrature
  - $S_3 = 2 \text{Im}(E_x E_y^*) \neq 0$

Output signal: circular $\pm 45^\circ$ linear

Eigenmodes of a spatial period $\Lambda$

- Eigenmodes of $n\Lambda$ long section can be anywhere on $S_2$-$S_3$ great circle

$\Lambda = \text{TE-TM beat length, } \sim 21 \mu m$ at 1550 nm wavelength
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

$\Lambda = 21 \mu$m
Speed problem of equalizers with more than one variable DGD section

- Scenario: additional DGD of 52 ps to be inserted in equalizer
- 1st possibility: DGD change 0 ... 52 ps = 10,000 \( \lambda \). At least one subsequent joint (polarization transformer) must rotate 10,000 times with 10 ... 100 steps/turn. \( \Rightarrow \) Speed problem! No PMD compensation with more than 1 section is possible with variable DGD sections!
- 2nd possibility: two fixed 26 ps DGD sections unfold \( \Rightarrow \sim 10,000 \) times faster

0 ps ................ 52 ps

10,000 turns (ERRORS!)

0 ps ... 52 ps
10,000 turns

DGD section joints

... unless joint(s) turn 10,000 times
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 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 $\sim$26ps/100mm is perfect at 40...80Gbit/s !
- First and higher-order PMD compensation on one chip !
- Higher electrooptic coefficient
- Polarization transformers are optimally oriented with respect to DGD sections ! (Endless polarization transformation from any polarization to linear in only one X-cut, Z-propagation LiNbO$_3$ waveplate is practically impossible.)
- No, or at least a substantially reduced DC drift !
Polarization control results

Continuous, endless polarization tracking on the 30 most critical great circles of the Poincaré sphere crossing the TE/TM “poles”. All other cases are better behaved.

Corresponding misalignment angle distribution, number of hits vs. angle in rad.

Tracking speed: 0.012 rad/iteration
**Practical problem**

- Long term (days to months) DC drift is a big problem in X-cut, \( Z \)-prop. \( \text{LiNbO}_3 \) polarization transformers due to the static field required to tune out residual waveguide birefringence.

- Although there is no static field in X-cut, \( Y \)-prop. \( \text{LiNbO}_3 \) a susceptibility to DC drift can not be ruled out.

⇒ Drive device with zero-mean signals to reduce/avoid DC drift!
DGD profile of a PMDC subject to DC drift, and 3 DGD profile instantiations of a PMDC protected against DC drift

Full mode conversion SBA with rotating orientation added at PMDC input. DGD profile is twisted. DC drift is avoided.

Static case, subject to DC drift.
Experiment performed with Siemens ICN

TX 20 Gbit/s → M → DGD 10ps → M → DGD 20ps → PMD compensator, 43ps → clock & data recovery → data out → photodiode → controller → (⋅)^2 → (⋅)^2

20Gbit/s PMD compensation with distributed PMD compensator

control on

log(BER)

clock & data recovery

data out

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$_3$ distributed PMD compensator

back-to-back

equalizer not working

equalizer working
40 Gbit/s CSRZ-DPSK transmission setup with distributed PMD compensation
Arrival time detection of PMD for 40 Gbit/s CSRZ-DPSK

Measurement interval: 2.4 μs
Sensitivity: ~1.2 ps
Spectra at integrator output with PMD compensator stopped or running
### Q factors measured for various configurations

| Q [dB] | back-to-back + scrambler | + PMDC | + 34km of fiber | + 2 DGD sections [ps] | or +6.2  
|--------|--------------------------|--------|-----------------|-----------------------|--------
| 26     |                          |        |                 |                       |        
| 24     |                          |        |                 | 4+4 6.6+6.2           |        
| 22     |                          |        |                 | 6.6+8.6 13.6+8.6      | or +6.2
| 20     |                          |        |                 |                       |        
| 18     |                          |        |                 |                       |        

Optical PMD compensation
Motivation for polarization division multiplex transmission

- Doubled fiber capacity
- $2 \times 40 \text{Gbit/s}$ NRZ polarization division multiplex tolerates more PMD than $80 \text{Gbit/s}$ NRZ single-channel transmission, and much more than polarization-interleaved $40 \text{Gbit/s}$ NRZ single-channel transmission with halved frequency spacing and polarizer at RX.
- $2 \times 40 \text{Gbit/s}$ PolDM tolerates more chromatic dispersion than $80 \text{Gbit/s}$.
- Distributed PMD compensator is able to output any desired polarization state $\Rightarrow$
  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

Information bits
Photocurrents
Polarization mismatch
Interchannel phase difference

$\psi$

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

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

\[ \eta \sim \pi \Delta f_{\text{peak-peak}} \tau = 4.2 . \]

54MHz 25ns
PMD tolerance of polarization division multiplex vs. 2-IM

- Non-interleaved NRZ PolDM supports same capacity $\times$ fiber length product.
- RZ and phase-shaped PolDM transmission reduce PMD tolerance.
- Note: System penalty [dB] $\approx 2 \times$ eye closure penalty [dB]
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](image)
Root mean square arrival time variation vs. DGD at 40Gbit/s

sensitivity 150fs, measured in 4.8μs
$2 \times 40 \text{Gbit/s, 212km polarization division multiplex transmission with endless polarization control and PMD compensation}$

- **FM**: 1541.6 nm
- **FM**: 1544.8 nm
- **CS-RZ**
- **20GHz**
- **MOD**
- **40Gbit/s**
- **MUX**
- **PT**
- **M**
- **VCO**
- **PI**
- **data out**
- **errors without PMDC**
- **NO ERRORS with PMDC**

Components:
- **DSF**: 33km, 15km, 51km, 50km
- **SSMF**: 63km
- **DCF**: 15km
- **Polarization & PMD controller**
- **POLARIZER**
- **DGD 4ps**
- **arrival time**
- **interference**

Connections:
- **PT**
- **MUX**
- **VCO**
RZ polarization division multiplex signals in the presence of interchannel phase modulation

Polarization crosstalk $\downarrow$
interference detection

PMD $\downarrow$
arrival time detection

A similar scheme exists also for NRZ polarization division multiplex.
Setup for demonstration of cross channel-induced nonlinear PMD in WDM system, L. Möller, L. Boivin, S. Chandrasekhar and L.L. Buhl, ELECTRONICS LETTERS, Vol. 37, No. 5, (306-308), March 2001

Limits due to fiber nonlinearity
Nonlinear polarization evolution induced by cross-phase modulation and its impact on transmission systems, B.C. Collings, L. Boivin, Photonics Technology Letters, Vol. 12, No. 11, 2000, pp. 1582-1584

Fig. 1. Orient Stokes vectors for the two signals. Labels show the Launch peak powers of each signal. Horizontal parted, the power is changed by 0.2 dBm.

Fig. 2. Schematic of the transmission line setup. (FPF: fiber polarization filter, RX: receiver, SSMF: standard single-mode fiber).

Fig. 3. Received bit patterns with the polarizer in front of the receiver for two different settings of the polarization controller. Arrows indicate large amplitude variations of the same bit.

Fig. 4. (a) Maximum extinction possible by the polarizer versus launched power per channel for: 1) a single modulated channel, 2) all channels unmodulated and 3) all channels modulated. (b) Measured Q factor versus launched peak power per channel for: 1) with and 2) without the polarizer in front of the receiver.
Principle of coherent optical transmission

- Operation point of the photodiodes is transferred from the apex of the parabolic field detection characteristic to a steeper part.

- Interference term provides linear electric field detection!

- Intermediate frequency ...
  - $|\omega_{IF}| \geq 1/(2T)$  Heterodyne
  - $|\omega_{IF}| = 0$  Homodyne
  - $1/T >> |\omega_{IF}| \geq 0$ „Intradyne“, needs I&Q or 3-phase optical receiver. With asynchronous detection: phase diversity

- Polarization matching required!

- $\psi = \text{angle on Poincaré sphere}$
Phase diversity, polarization diversity, polarization division multiplex, electronic polarization control, PMD, PDL and CD compensation

Multiplication by Jones matrices cascaded with DGD sections, which together represent inverse DGD profile of fiber:

Complete purely electronic polarization control, PMD, PDL and CD compensation
Taylor series expansion of PMD vector is unphysical because PMD changes quasi periodically as a function of frequency.

If Taylor series is used: Categorize various orders of PMD depending on their relation to the input polarization.

<table>
<thead>
<tr>
<th>Order</th>
<th>Parallel to input polarization</th>
<th>Perpendicular to input polarization: mix of opposed parallel cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>delay</td>
<td>symmetric eye closure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(depends on fiber CD)</td>
</tr>
<tr>
<td>2</td>
<td>(2nd-order) CD, adds to fiber CD, symmetric overshoot, curvature difference</td>
<td>vertically asymmetric, horizontally symmetric eye closure</td>
</tr>
<tr>
<td>3</td>
<td>3rd-order CD, slope steepness difference, asymmetric overshoot</td>
<td></td>
</tr>
</tbody>
</table>

Higher-order PMD description
A frequency-independent mode conversion at the fiber input. This is described by 2 parameters, for example retardation and orientation of an SBA.

A total DGD.

A frequency-independent mode conversion at the fiber output. In the general case a mode conversion (2 parameters, as at the input) and a differential phase shift (one more parameter) are needed. In total this means that there is a frequency-independent elliptical retarder at the output.

Complex Fourier coefficients $F_k$ of mode coupling along the birefringent medium, which exhibits the above total DGD only in the absence of mode conversion.

$$F_k = \int_0^L \left( \frac{d\varphi(z)}{dz} e^{j\psi(z)} \right) e^{-j2\pi k z/L} dz$$

Soleil-Babinet analog (SBA)
retardation orientation
($=\text{bend angle}$) ($=\text{bend orientation}$)
Order and number of real parameters in higher-order PMD definition methods

<table>
<thead>
<tr>
<th>Method (below) and its order (right)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taylor expansion of PMD vector (TEPV, Jones matrix given by Heismann)</td>
<td>3</td>
<td>6</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Exponential Jones matrix expansion (EMTY = Eyal, Marshall, Tur, Yariv)</td>
<td>3</td>
<td>6</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Sequence of DGD sections (SDGD)</td>
<td>3</td>
<td>5</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Fourier expansion of mode coupling (FEMC)</td>
<td>3</td>
<td>5</td>
<td>9</td>
<td>13</td>
</tr>
</tbody>
</table>

1st-order PMD, identical for all methods

\( F_0 \), uniform bending of DGD profile

\( F_{-1}, F_0, F_1 \), more complicated bending of DGD profile

3 extra parameters are needed for all methods if frequency-independent output polarization transformation needs also to be described.
DGD profile of an exemplary PMD structure, cascaded with inverted FEMC structures

PMD device to be characterized

- Cascaded with inverted 1st-order structure
- Cascaded with inverted 2nd-order FEMC structure
- Cascaded with inverted 3rd-order FEMC structure
Extinction of cross polarization at output of PMD device cascaded with inverted 3rd-order FEMC structure

Gaussian input pulse width is chosen equal to total DGD of FEMC structure after convergence of search algorithm.

Search algorithm maximizes cross polarization extinction.

Ideal PMD description would result in infinite cross polarization extinction.

(Time is rescaled by factor 16 compared to previous viewgraph.)
Suppression of cross polarization by equalizers (= inverted structures) defined by higher-order PMD definition methods

<table>
<thead>
<tr>
<th>Method order</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian input pulse width [a.u.]</td>
<td>5.6</td>
<td>7.2</td>
<td>9.5</td>
</tr>
<tr>
<td>Taylor expansion of PMD vector (TEPV)</td>
<td>10.3 dB</td>
<td>14.8 dB</td>
<td>19.9 dB</td>
</tr>
<tr>
<td>Exponential Jones matrix expansion (EMTY)</td>
<td>10.3 dB</td>
<td>12.6 dB</td>
<td>16.1 dB</td>
</tr>
<tr>
<td>Fourier expansion of mode coupling (FEMC)</td>
<td>10.3 dB</td>
<td>21.6 dB</td>
<td>35.5 dB</td>
</tr>
</tbody>
</table>

- dB and pulse width values are averaged over 75 PMD examples.
- Pulse widths are chosen equal for all methods, using the value obtained after convergence of FEMC for one particular order. Part of extinction improvement of high method orders is due to broader pulses.

Extinction improvement of higher-order FEMC over 1st-order PMD seems to be ≥2 times larger (in dB) than that of TEPV or EMTY!

- Reason: FEMC (and SDGD) are closely related to natural PMD, unlike higher-order TEPV and EMTY.

- Drawback: Finding FEMC coefficients is a numerical optimization process ⇒ more research is needed.
Conclusions (1): My PMD compensation philosophy

- Electrical compensation: Low-cost compromise, to be used at 10 Gbit/s.
- Electrical detection: Low-cost, high performance.
  - Arrival time detection (example: $2.4\mu s$, sensitivity $\sim 1$ ps @ 40 Gbit/s)
  - Slope steepness detection
  - 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.

  - Distributed PMD compensator in X-cut, Y-prop. LiNbO$_3$ has various advantages over other PMD compensators:
  - Polarization transformers and DGD sections are integrated on one chip.
  - Endless polarization transformations of any polarization state into PSP of DGD section
  - DC drift is much less problematic than in X-cut, Z-prop. LiNbO$_3$ polarization transformers.
Conclusions (2): Difficulties in implementing PMD compensation

- Fast endless polarization control = 60%
- PMD and polarization mismatch detection = 30%
- PMD theory = 10%
- Go or no go: XPM-induced polarization modulation is dangerous in the case of intensity-modulation or NRZ signalling. RZ-DPSK is tempting.

Yet more theory :-( Fourier expansion of mode coupling (FEMC) improves higher-order PMD description.

Most of this material can also be found in R. Noé et al., „PMD in High-Bit-Rate Transmission and Means for Its Mitigation“, IEEE JSTQE 10(2004)2, pp. 341-355, and its references.