Development of an Adaptive Polarization-Mode Dispersion Compensation System

Master's Thesis Defense

by

Arun-Prasad Chimata

Advisor: Dr. Christopher Allen

Dr. Kenneth Demarest Dr. Rongqing Hui

Department of Electrical Engineering and Computer Science

University of Kansas

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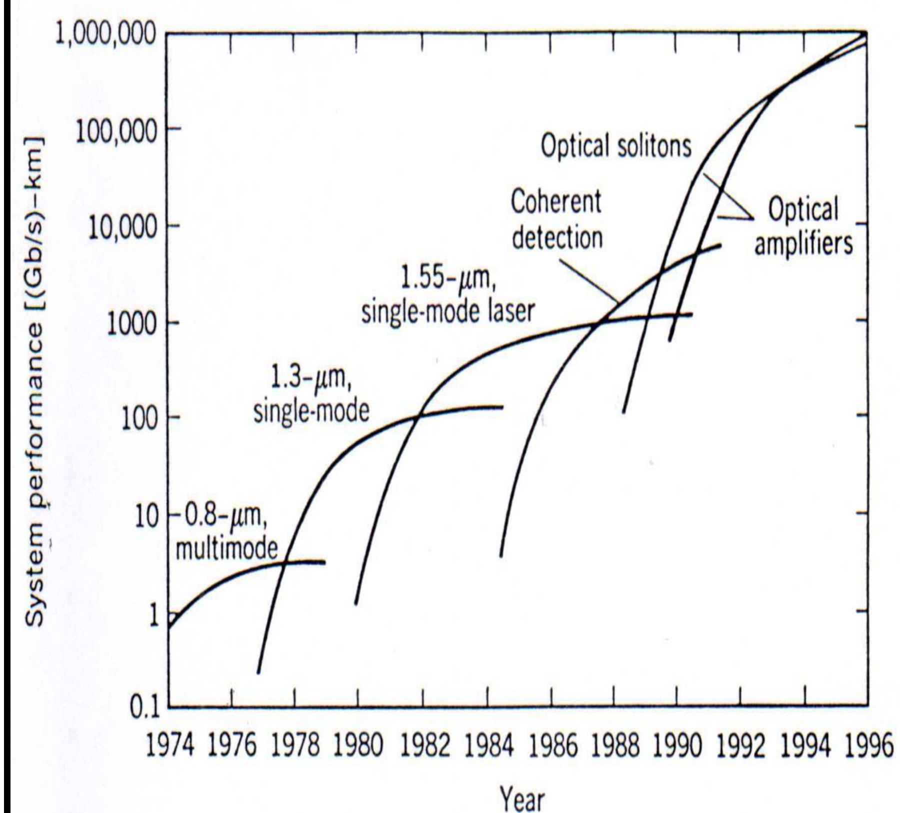
Outline

- Motivation
- Introduction to Polarization-Mode Dispersion (PMD)
- Overview of PMD Mitigation Approaches
- Adaptive PMD Compensation System Developed in KU
- Experiments, Inferences and Field Trial
- Summary and Conclusions
- Scope for Future Work

Motivation

- Fiber-optic technologies have enabled today's high-speed telecommunication capabilities
- Many hurdles crossed (e.g., attenuation, chromatic dispersion)
- Specialized fiber manufacturing methods evolved to reduce fiber deformities
- Still, at some bit-rate-distance product, system capabilities will be limited by PMD
- Compensation for effects of PMD is a solution

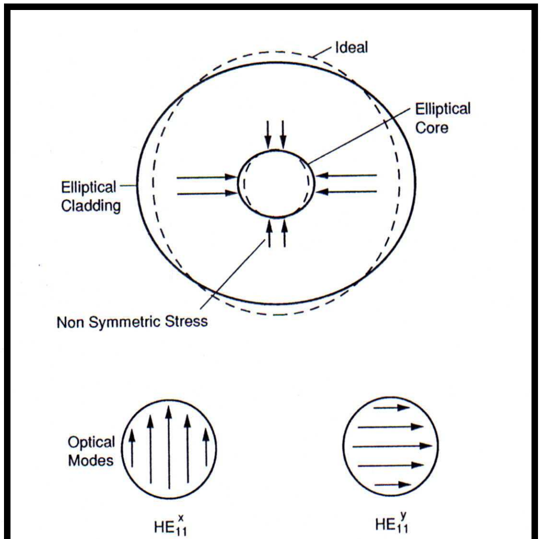


Growth of fiber-optic system capabilities since 1974

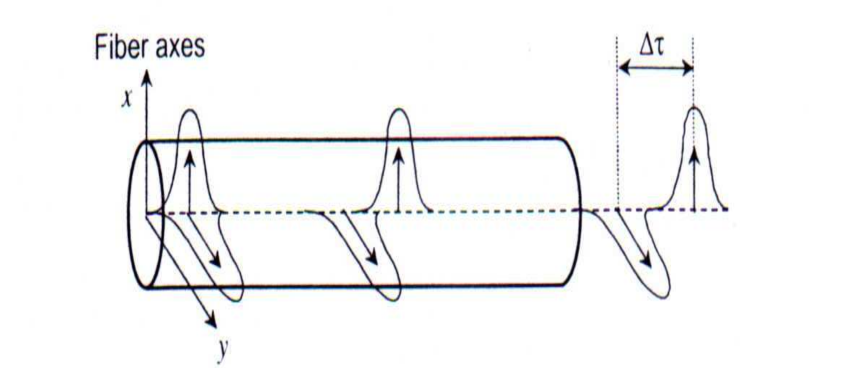
Introduction to PMD

Origins of PMD

- Single-mode fiber actually has two modes for light propagation due to asymmetry of core cross-section
- External stresses and inherent deformities cause asymmetry
- Propagation constants along the two modes are different: birefringence
- Components of an optical signal traveling along the two modes are differentially delayed at output. This delay is called Differential Group Delay (DGD)
- An input optical pulse arrives broadened at output: this effect is commonly called PMD



Fiber cross-section



DGD (Δτ) in a short fiber segment

Introduction to PMD

PMD in lengthy fiber spans: Principal States model

•Lengthy fiber spans (telecom grade) experience random stresses along the length causing mode-coupling. PMD effect is unpredictable.

•Principal states model proposed to model PMD in lengthy fiber spans

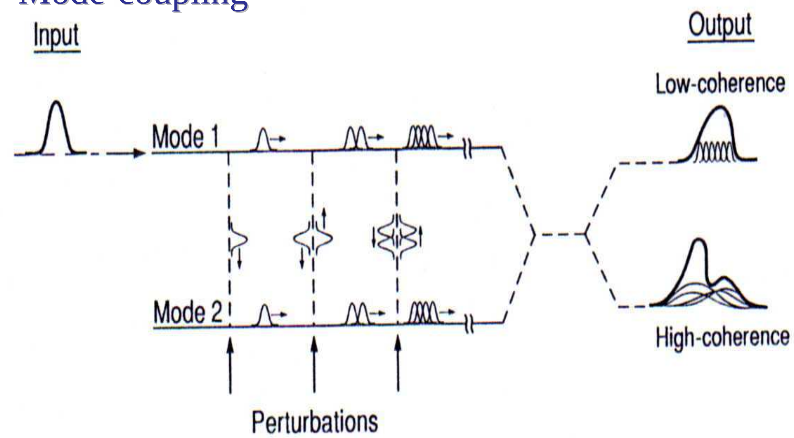
•Every fiber has a set of two orthogonal polarization states called Principal States of Polarization (PSPs) that yield an unchanged pulse shape at output.

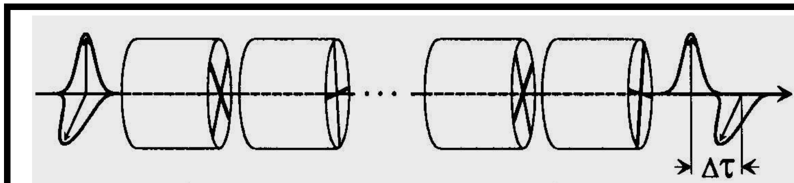
•Valid for a small frequency range only (i.e. PSPs change with optical frequency). PSPs vary with length and with time also.

• PMD vector has DGD as magnitude and PSP orientation as direction

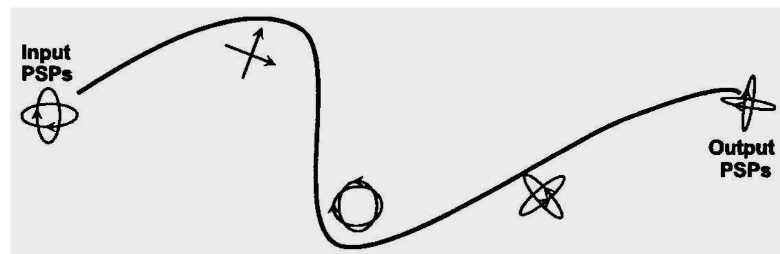
$$\vec{\tau} = \Delta\tau \, \hat{p}$$

Mode-coupling





Mode-coupling model of lengthy fiber span



Evolution of PSPs along length of a fiber span

Introduction to PMD

Effects of PMD

- PMD causes ISI in digital fiber-optic systems and distortion in analog lightwave systems

- PMD-induced power penalty, (dB) in digital systems is:

$$\varepsilon \cong A \frac{\Delta\tau^{2}\gamma(1-\gamma)}{T^{2}}$$

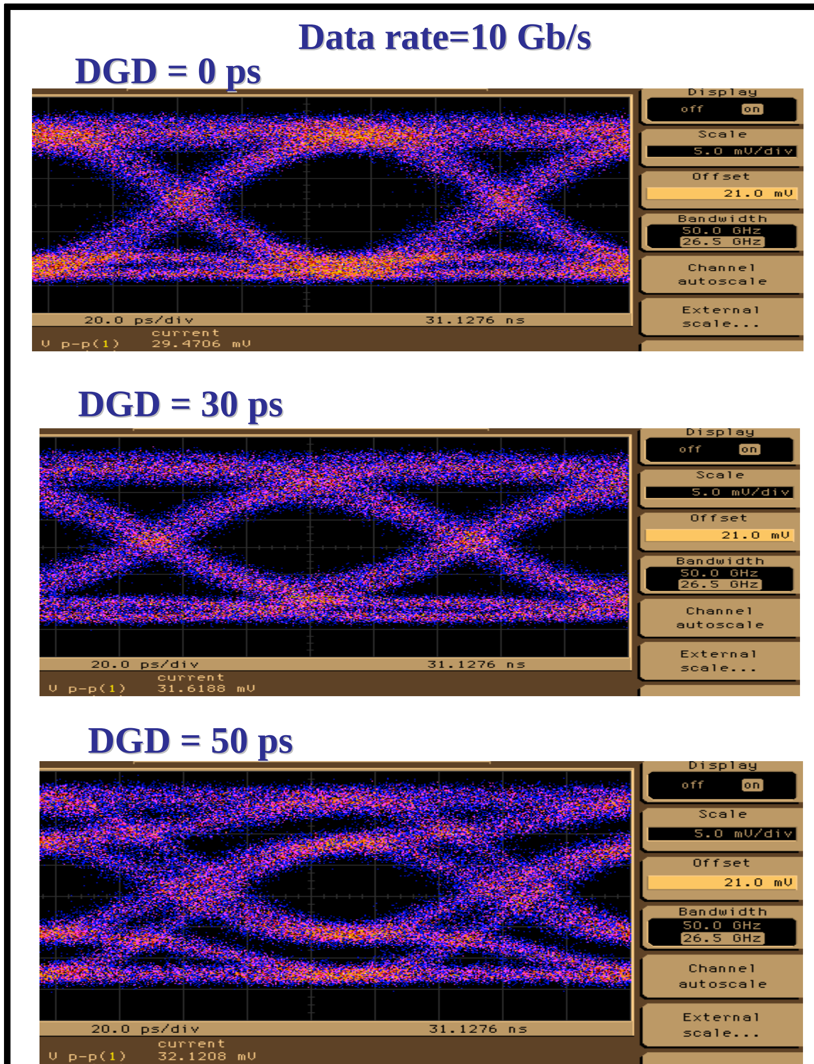
A : pulse-shape dependent constant

: ratio of power-splitting between the two modes

(0<= <= 1)

$\Delta\tau$ *: DGD (ps)*

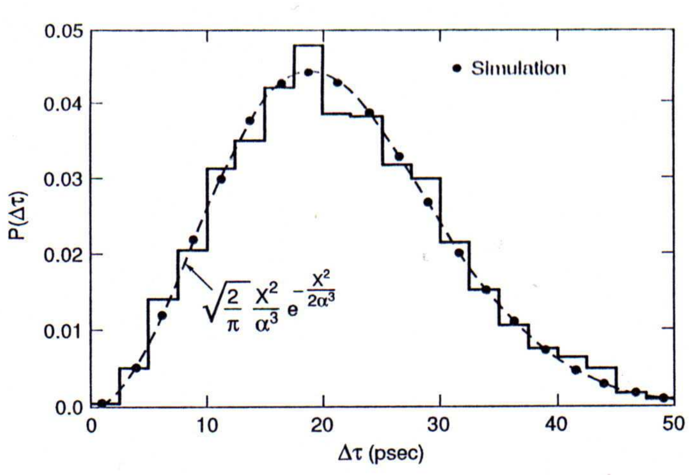
T : FWHM of lightwave pulse (bit-rate dependent)



Introduction to PMD

PMD statistics and higher order PMD

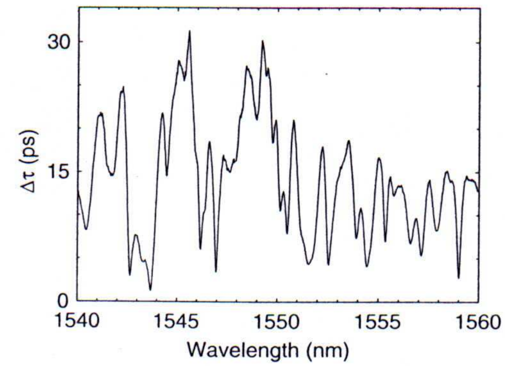
- DGD follows a Maxwellian probability distribution (over time and over wavelength)



Measured DGD distribution in 10 km of spooled fiber (subjected to temperature changes) and the Maxwellian fit

- Higher order PMD caused due to frequency dependence of DGD and PSPs

- Higher order PMD effects require consideration as bandwidth increases (e.g., 40 Gb/s data rate and beyond) and also in WDM systems



Measured DGD of a 14.7 ps mean DGD fiber, over wavelength

Overview of PMD Mitigation

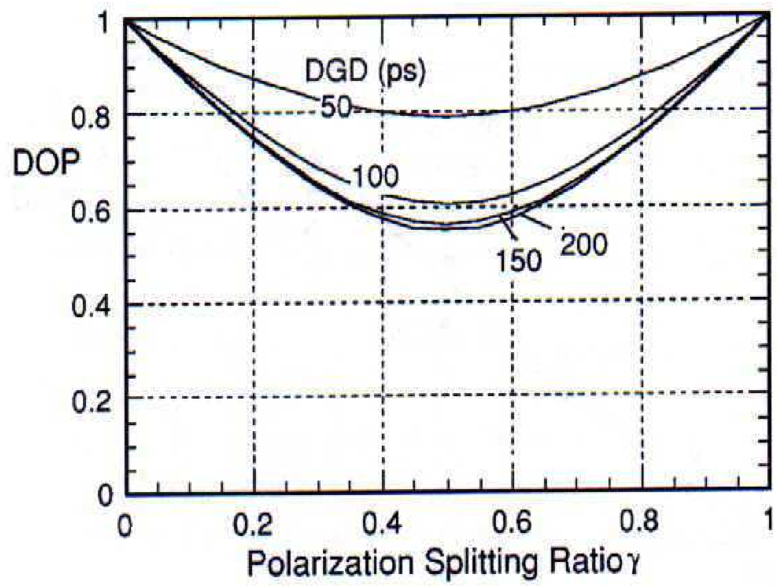
Overview of PMD compensation techniques

PMD monitoring techniques

1) RF power levels of specific tones in the received base-band spectrum
2) Degree of polarization (DOP) of the received optical signal
3) Received signal bit-error-rate (BER) or eye-diagram analysis

PMD-induced power penalty

$$\varepsilon \cong A\frac{\Delta\tau^2\gamma(1-\gamma)}{T^2}$$



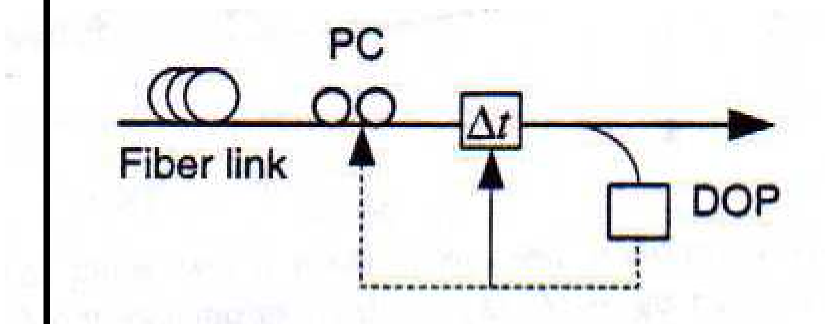
Simulated DOP vs , the ratio of power splitting between the two PSPs, for different DGD values (NRZ modulation, 10 Gb/s data rate)

Overview of PMD Mitigation

Overview of PMD compensation techniques

Components in a PMD compensation system:

- Polarization controller (PC)
- Delay element (variable or fixed)



PMD compensation concept (PC: polarization controller, Δt: variable delay element)

PMD compensation schemes:

- Half-order PMD compensator. Consists of a PC and a fixed delay element
- First-order PMD compensator. Consists of a PC and a variable delay element
- Second-order PMD compensator. Consists of two (or more) PCs and two (or more) delay elements

Overview of PMD Mitigation

Alternative approaches

• **Electronic equalization:**

a) ISI reduction at the receiver using electronic equalizers (transversal filter, decision-feedback equalizer)

b) Implementing electronic PMD mitigation techniques becomes challenging at high data rates.

• **Increasing PMD tolerance of a fiber-optic system**

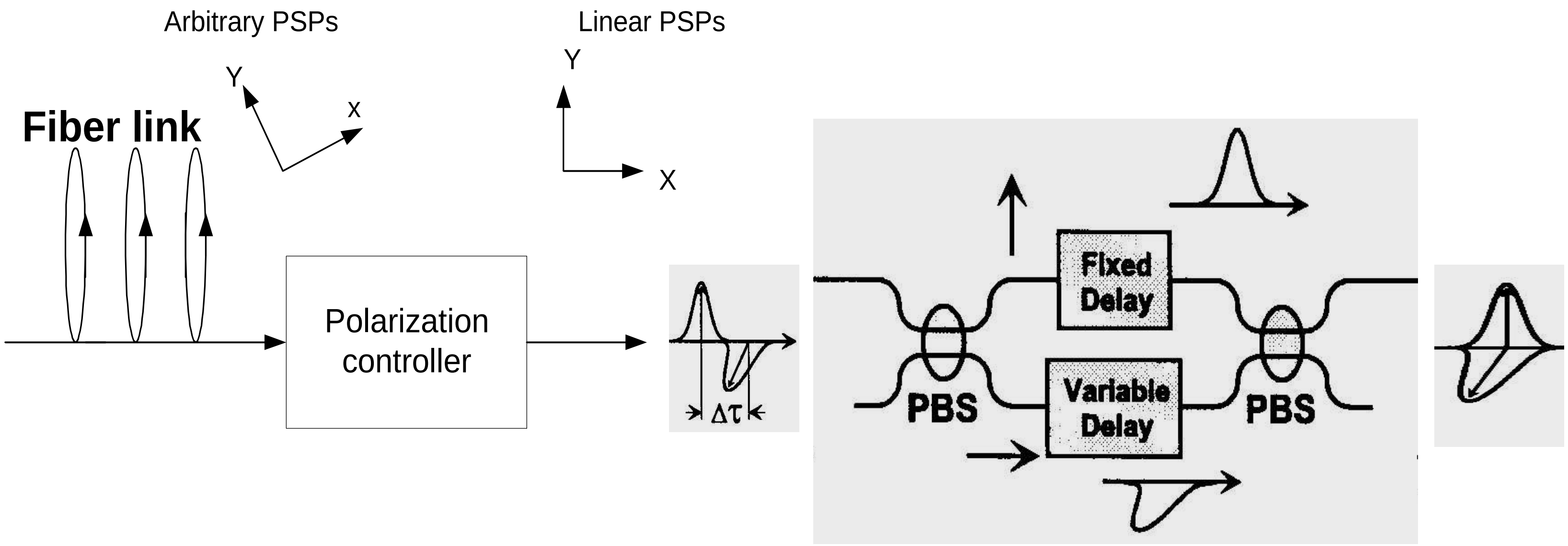
a) PMD resistant modulation formats (return-to-zero (RZ), chirped-RZ, dispersion-managed solitons).

b) Forward-Error Correction coding (FEC)

Adaptive PMD Compensation in KU

Development of the adaptive PMD compensation system

• Concept: Generation of a complementary PMD vector at the receiver (post-compensation) so that the effective PMD (link+compensation system) is zero

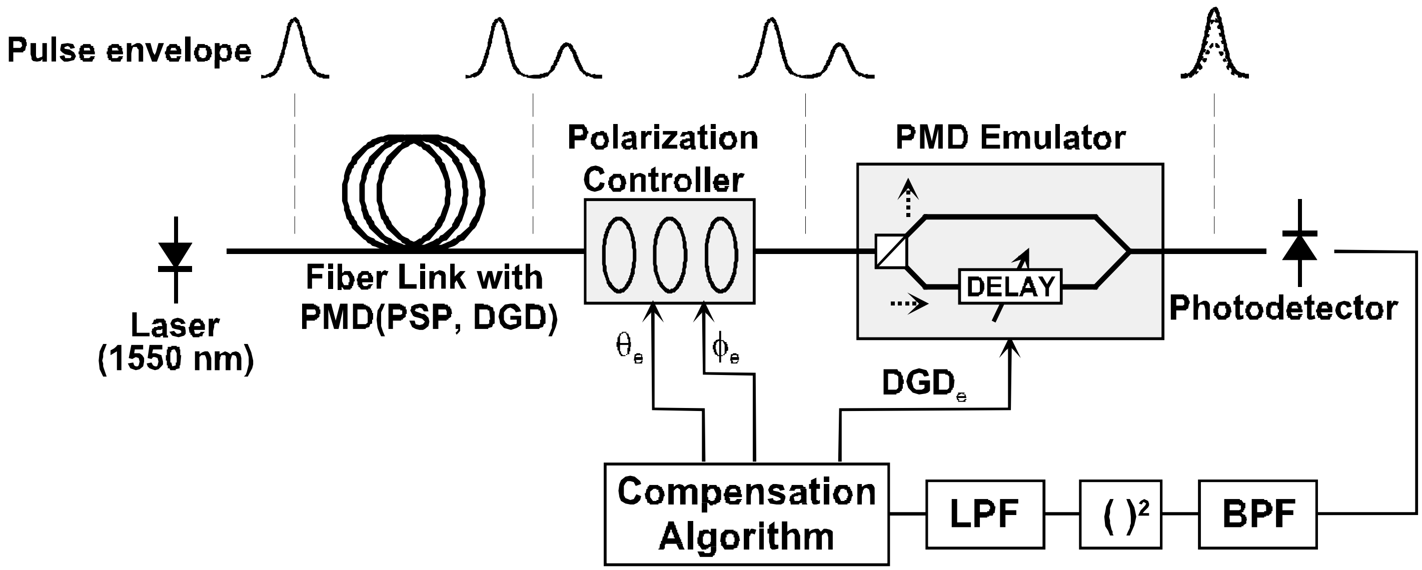


PBS: Polarization beam-splitter

Adaptive PMD Compensation in KU

Development of the adaptive PMD compensation system

- Early version of the PMD compensation system used power level of 5 GHz tone of the received base-band spectrum for PMD monitoring
- Polarization controller (PC) : HP-11896A; delay adjustment: JDS™ PE3 PMD emulator



Adaptive first-order PMD compensation system (LPF, BPF : low-pass and band-pass filters, $(\ )^2$: square-law detector, and : control parameters for PC)

Adaptive PMD Compensation in KU

Development of the adaptive PMD compensation system

- Enhancements:
  1) PC: high-speed device (E-TEK™) having 4 liquid-crystal cells
  2) Delay element: Santec™ variable delay line
  3) Dedicated micro-controller and interface board to provide control signals for operating the PC and delay line

- **PMD compensation algorithm:**
  1) Initialize PC cells and delay-line (PC cells set in their center positions and delay-line set at 0 ps)
  2) Introduce known amount of delay in delay-line
  3) Perform a coarse polarization search using the PC cells
  4) Perform a fine polarization search
  5) Perform a coarse delay search using delay-line; obtain initial estimate of delay
  6) Perform a fine delay search about the initial estimate of delay and obtain final delay value
  7) Observe PMD monitor signal (tracking of variation of PSPs and DGD)
  8) If threshold exceeded, perform one fine polarization search and one fine delay search
  9) Go to step 7

Adaptive PMD Compensation in KU

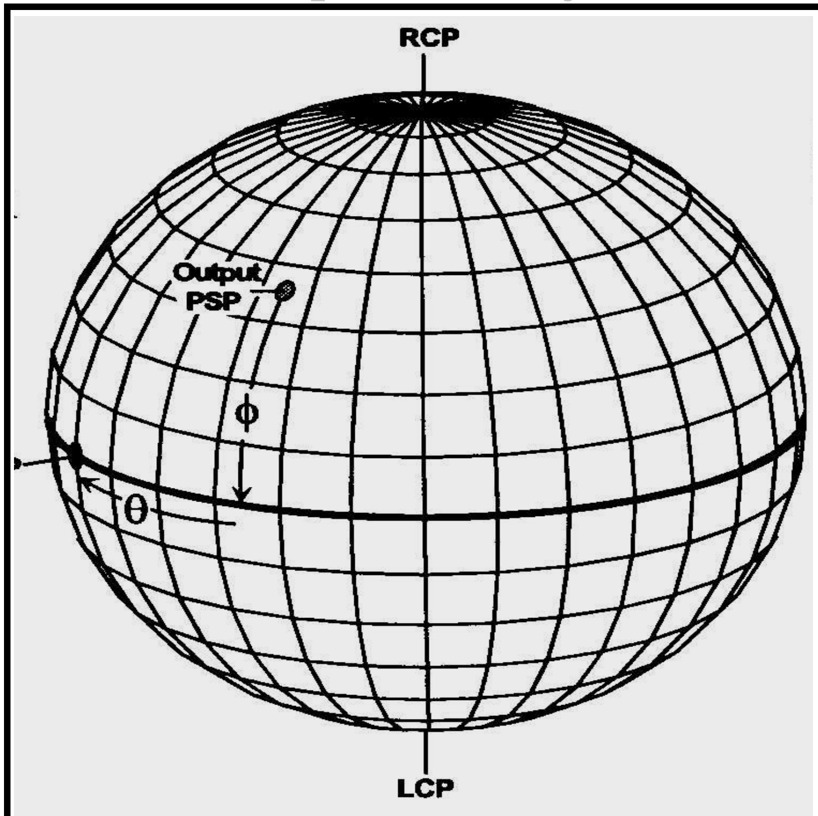
Development of the adaptive PMD compensation system

Operation and control of PC

- PC cells transform the output PSPs of the link to align with the input PSPs of the PBS
- E-TEK™ device has four cells, of which three are used
- Cells receive analog voltages from interface board

Operation and control of delay-line

- Delay-line receives a 11-bit digital code from the interface board for setting delay
- Resolution is 0.167 ps/step (maximum of 1800 steps and delay range is 300 ps)

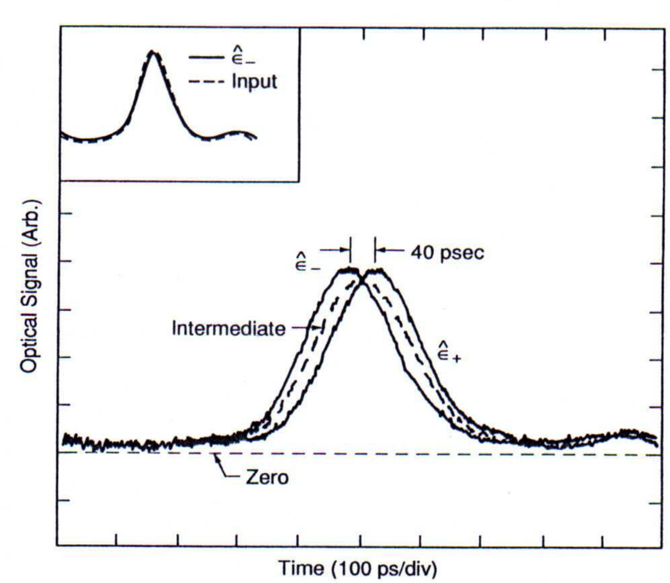


Poincare sphere representation of the polarization transformation performed by the PC (RCP, LCP: right circular and left circular polarization)

Adaptive PMD Compensation in KU

Polarization scrambling and PMD compensation

- PSPs orientation change with time
- State of polarization of optical signal is scrambled (randomly changed) before fiber-link so that —> 0.5
- Required to obtain reliable estimates of the PSPs and DGD during PMD compensation
- Significance first studied and demonstrated in KU-lightwave lab. Fiber-squeezer type polarization controller currently used for scrambling
- Scrambling frequency must be higher than sampling frequency of PMD compensator
- Compensation algorithm uses average of many samples of monitor signal. This effect is similar to the case when = 0.5 (true extent of PMD assessed)



Measured DGD due to PMD in 10 km of dispersion-shifted fiber

PMD-induced power penalty

$$\varepsilon \cong A \frac{\Delta\tau^2 \gamma (1-\gamma)}{T^2}$$

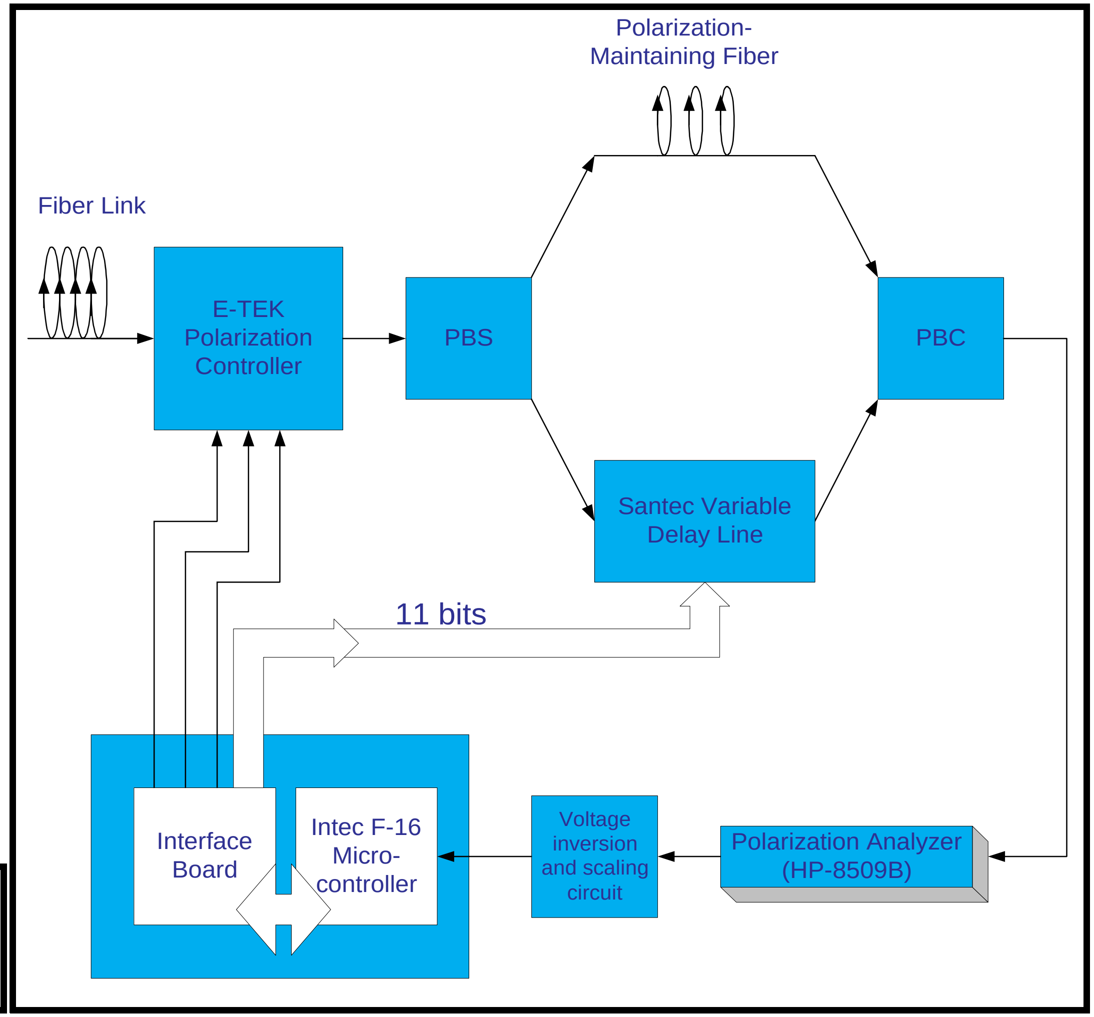
Lightwave Laboratory
The University of Kansas/ITTC

Information and Telecommunication Technology Center

Adaptive PMD Compensation in KU

Degree of polarization (DOP) based PMD monitoring

- DOP-based PMD monitoring is bit-rate independent
- Largely modulation format independent. To a good extent reduces hardware complexity.
- Present PMD monitoring is based on DOP of received optical signal.
- Analog equivalent of DOP used as PMD monitor signal.



Adaptive PMD compensation with DOP-based PMD monitoring. (PBS, PBC: polarization beam splitter and combiner)

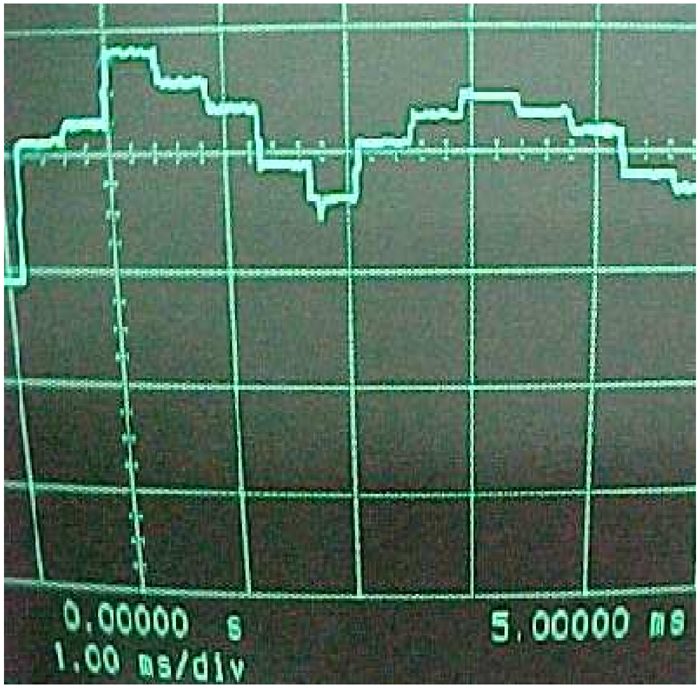
Experiments, Inferences and Field Trial

Operating speed of PMD compensator:

- Time taken for one complete compensation cycle is 100 s

Scrambling frequency test:

- DOP measurement affected by polarization scrambling
- Scrambling frequency range chosen so as to cause minimal interference to DOP measurement (i.e. kept much lower than measurement sampling rate)
- Still, frequency must be higher than PMD compensator sampling rate
- Present DOP measurement sampling frequency is 2500 Hz
- Sampling frequency of PMD compensator is 50 Hz
- Scrambling frequency range between 80 Hz and 100Hz

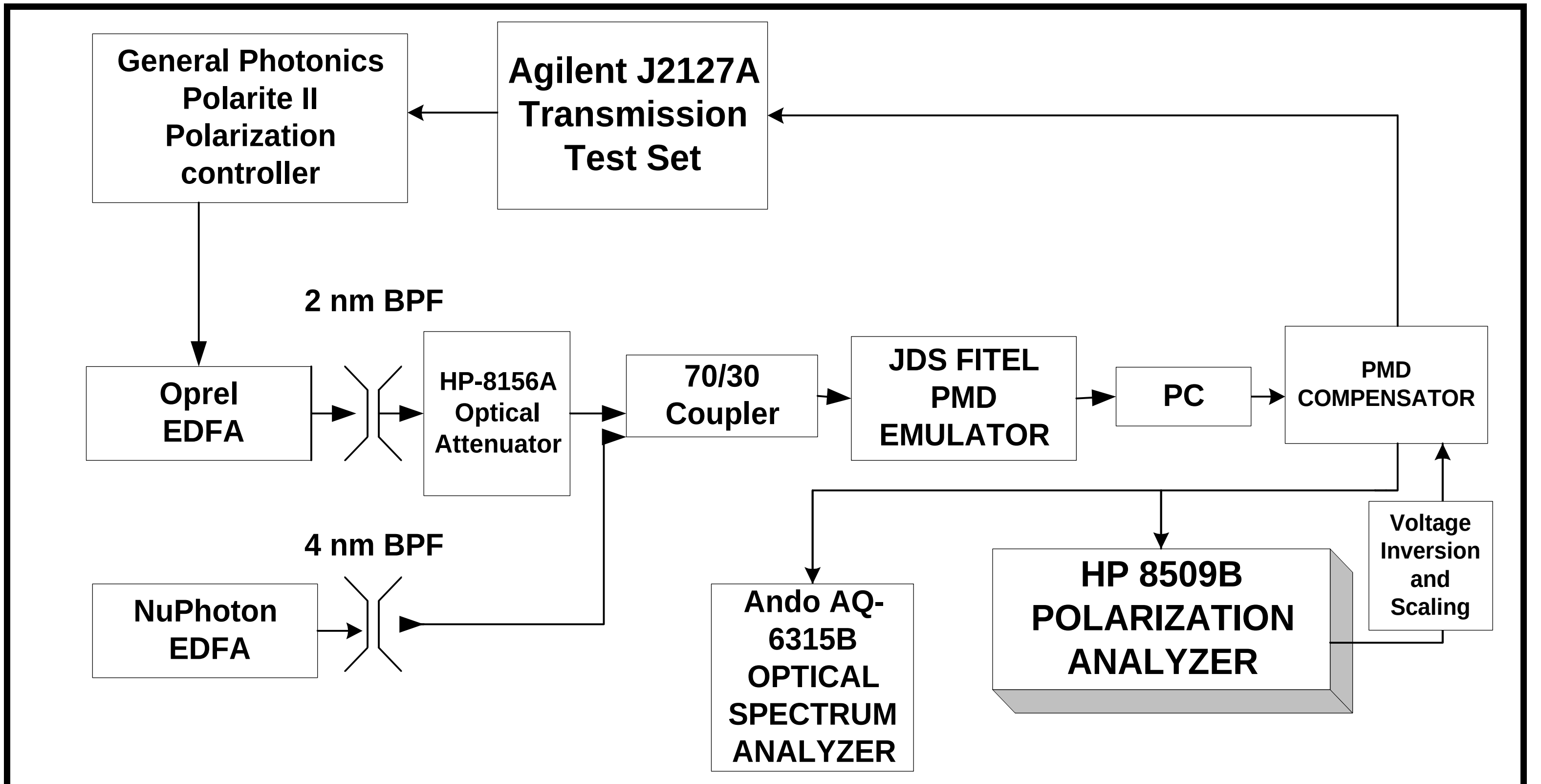


Display of DOP analog voltage (as measured by HP-8509B polarization analyzer). Obtained by scrambling at 1 kHz.

Experiments, Inferences and Field Trial

Optical signal to noise ratio (OSNR) test on the PMD compensator

- To find out the minimum received OSNR at which the PMD compensator can compensate satisfactorily
- Helpful in assessing PMD compensator's performance in multi-span, amplified, lightwave communication systems



OSNR test set-up (PC: paddle-type polarization controller; BPF: band-pass filter)

Experiments, Inferences and Field Trial

Procedure:

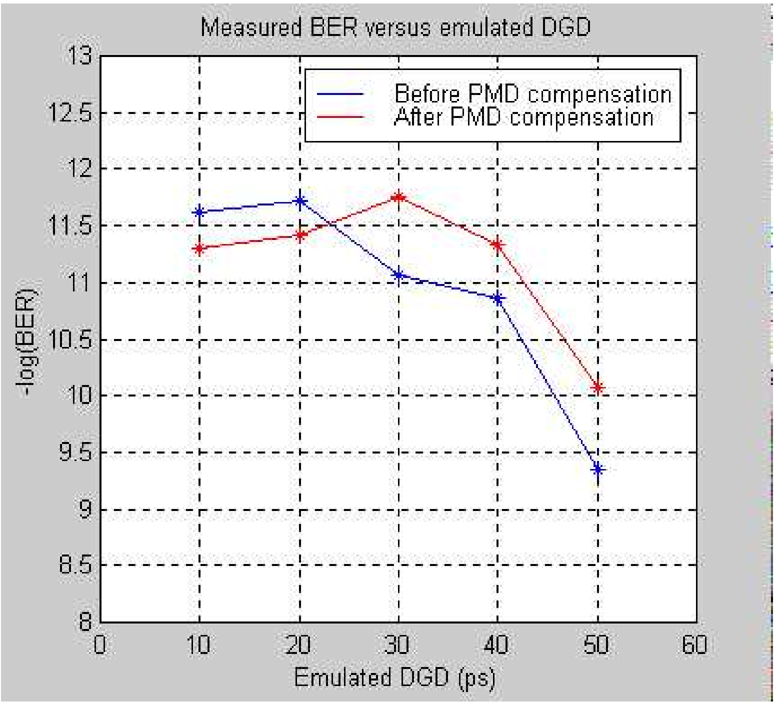
- OSNR measured and fixed
- Bit error rate (BER) measured with 0 ps DGD (emulated)
- BER measured with finite DGD (emulated)
- PMD compensation cycle run
- Post-compensation BER measured and compared
- Repeated with different DGD
- Repeated with different OSNR

Measured BER with 0 ps DGD (emulated) and with compensator in initial conditions

OSNR (dB)	***Measured BER***
4	1.175e-5
6	3.201e-7
8	3.406e-9
10	1.043e-12

Experiments, Inferences and Field Trial

Comparison of measured BER obtained before and after PMD compensation for different DGD values (OSNR = 10 dB)



Conclusion:

- PMD compensation system can perform satisfactory compensation at OSNR values of 10 dB and higher

Experiments, Inferences and Field Trial

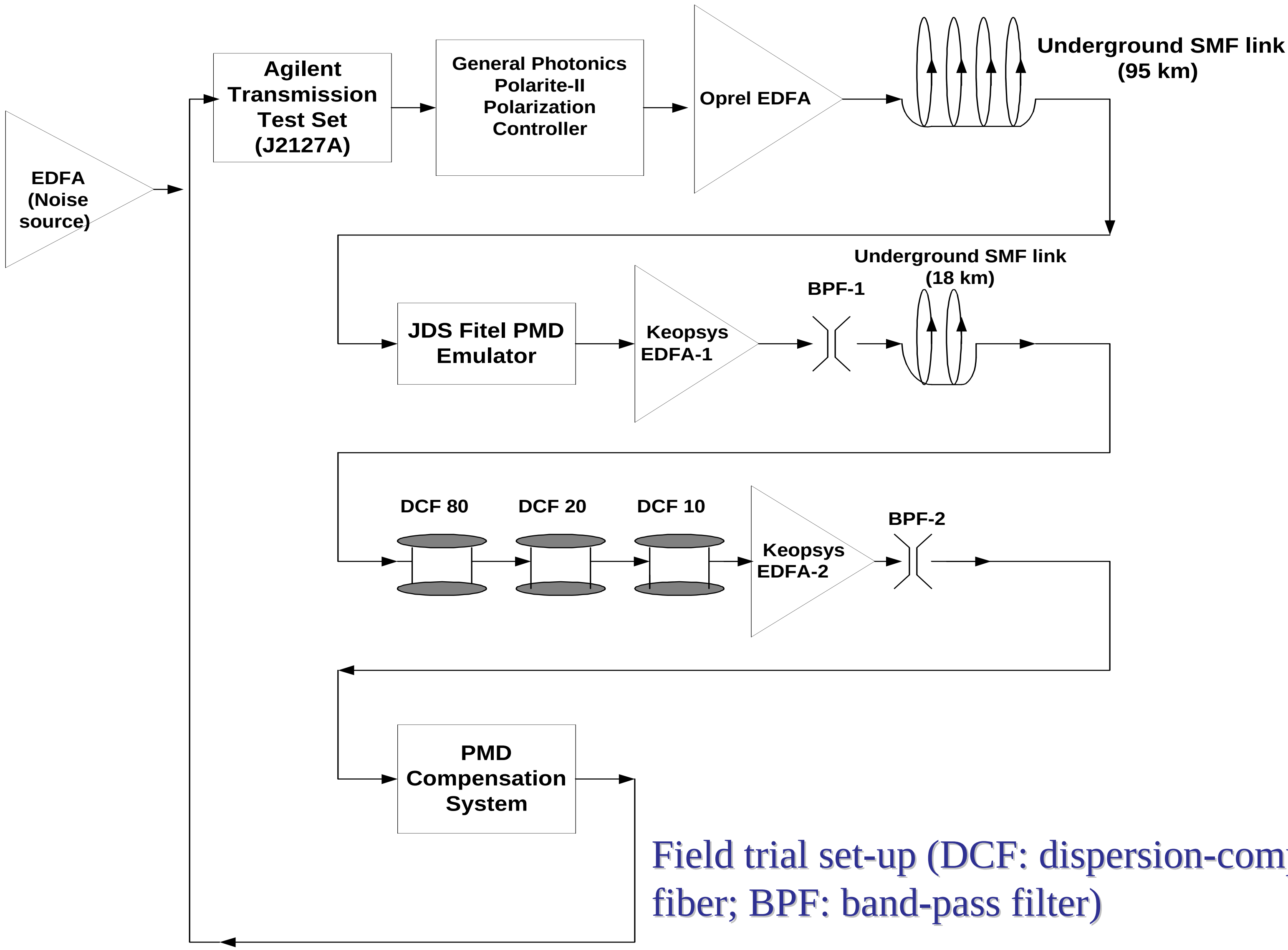
Field trial of the PMD compensation system

- To test the PMD compensation system on an underground fiber-optic link
- Link length ~ 95 km
- Chromatic dispersion measured to be ~ 1550 ps/nm at 1534 nm. Necessitated chromatic dispersion compensation.
- Power budgeting performed to minimize impact of optical amplifier noise

System parameters:

- Operating wavelength: 1534 nm
- Data rate: 10 Gb/s
- Waveform: NRZ (non return to zero)
- Bit sequence: PRBS (pseudo-random bit sequence), 2^{23}-1

Experiments, Inferences and Field Trial



Field trial set-up (DCF: dispersion-compensating fiber; BPF: band-pass filter)

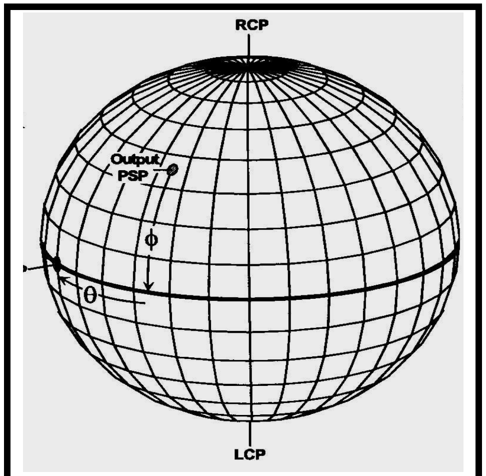
Experiments, Inferences and Field Trial

Number of scrambling axes versus PMD compensation performance:

- Number of polarization scrambling axes can be one or more
- One-axis scrambling changes the state of polarization (SOP) over one great circle on Poincare sphere
- Two or more axes provide more complete coverage on the Poincare sphere
- Test to find if the number of scrambling axes affected PMD compensation performance

Procedure:

- Emulate a finite value of DGD using emulator
- Perform PMD compensation with one-axis scrambling
- Measure post-compensation BER
- Perform PMD compensation with four-axis scrambling
- Measure post-compensation BER
- Compare BER values
- Repeat as necessary



Poincare sphere

Experiments, Inferences and Field Trial

Measured BER for emulated DGD of 0 ps and 30 ps

Emulated DGD (ps)	Measured BER
0	6.26e-12
30	3.085e-11

Compensation performance with 4-axis scrambling (emulated DGD=30 ps)

Trial	Compensated DGD (ps)	Measured BER
1	26	3.826e-12
2	24	2.426e-12

Compensation performance with 1-axis scrambling (emulated DGD=30 ps)

Trial	Compensated DGD (ps)	Measured BER*
1	37	2.773e-12
2	24	4.159e-12

* SOP before the PMD emulator adjusted during BER measurement

Conclusion:

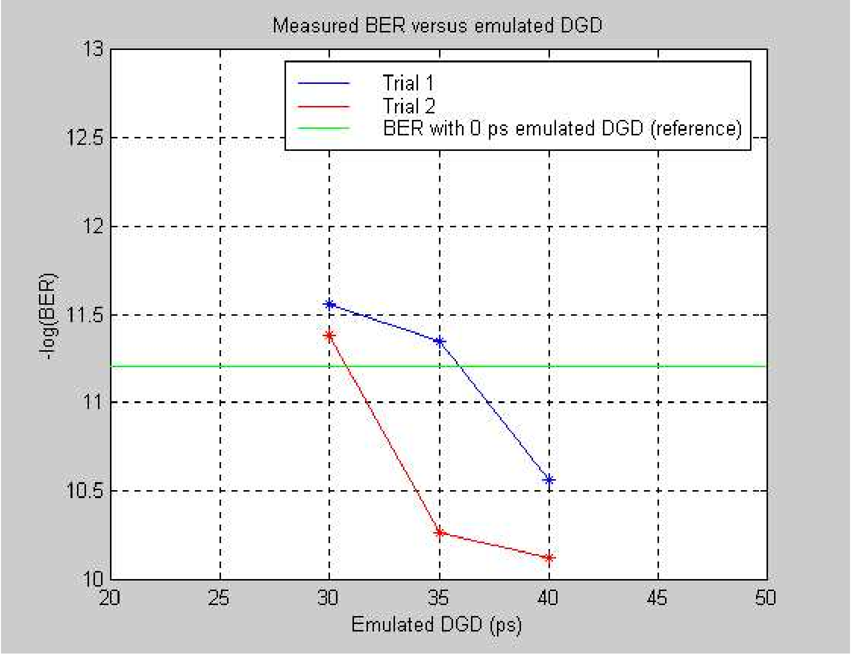
PMD compensation performance is independent of number of axes of scrambling

Experiments, Inferences and Field Trial

Maximum DGD the PMD compensation system can compensate for

- Emulated DGD increased from 30 ps upward. DGD at which PMD compensation performance degraded was determined.

Comparison of BER measured after PMD compensation for different emulated DGD values



Conclusion:

PMD compensation system can compensate for up to a maximum DGD of 40 ps

Experiments, Inferences and Field Trial

Scrambling frequency versus PMD compensation performance

- To demonstrate the importance of scrambling frequency
- Single-axis scrambling performed. Scrambling frequency varied from 5 Hz through 1300 Hz
- 30 ps of DGD emulated for all trials
- At each scrambling frequency setting, PMD compensation performance was determined
- Degree of polarization (DOP) measurement sampling rate ~ 2500 Hz
- Measured BER with 0 ps emulated DGD was 6.26×10^{-12} (reference BER)

Experiments, Inferences and Field Trial

Measured BER after PMD compensation with different polarization scrambling frequencies (PMD compensator sampling frequency of 50 Hz; reference BER of 6.26e-12)

Scrambling frequency (Hz)	Compensated DGD (ps)	Measured BER
5	26	2.052e-11
10	44	4.571e-10
20	35	1.148e-11
50	15	2.156e-11
80	35	2.087e-12
100	36	3.826e-12

Experiments, Inferences and Field Trial

Measured BER after PMD compensation with different polarization scrambling frequencies
(PMD compensator sampling frequency of 100 Hz; reference BER of $\approx 10^{-13}$)

Scrambling frequency (Hz)	Compensated DGD (ps)	Measured BER	Comments
200	26	6.608e-12	Lengthy tracking
400	36	3.3e-13	Lengthy tracking
700	36	1.009e-11	-
1200	19	2.504e-11	Lengthy tracking
1300	25	1.461e-11	Lengthy tracking

Experiments, Inferences and Field Trial

Conclusion:

- PMD compensation performance degrades when polarization scrambling frequency is less than the sampling rate of PMD compensation system

- Also, performance degrades when scrambling frequency approaches the DOP measurement sampling rate. In addition, tracking cycles are initiated too often (lengthy tracking).

- Optimum scrambling frequency range: **80 Hz – 100 Hz**

Summary and Conclusions

- An adaptive PMD compensation system was modified into a robust and bit-rate-independent one.
  - DOP-based PMD monitoring incorporated.

- Time taken for one complete compensation cycle was determined to be 100 s

- OSNR tests conducted on PMD compensation system. Satisfactory compensation performance at received OSNR values of 10 dB and higher.

- Field trial of the PMD compensation system successfully performed on an underground fiber-optic link

- PMD compensation performance determined to be independent of the number of axes of polarization scrambling

- Limit of PMD compensation system identified to be about 40 ps of DGD.

- Importance of polarization scrambling frequency experimentally verified

Scope for Future Work

- Replacement of the HP-8509B Polarization Analyzer with a compact, high-speed DOP measurement device
- Testing PMD compensation system at 40 Gb/s data rate
- Evaluation of PMD compensation performance in mitigating second-order PMD effects
- Testing PMD compensation system performance for RZ (return-to-zero) format

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THANK YOU