Polarization Mode Dispersion and Its Mitigation Techniques in High Speed Fiber Optical Communication Systems

Chongjin Xie

Bell Labs, Lucent Technologies

791 Holmdel-Keyport Road, Holmdel, NJ 07733

WOCC'2005, April 22, 2005, Newark, NJ

Outline

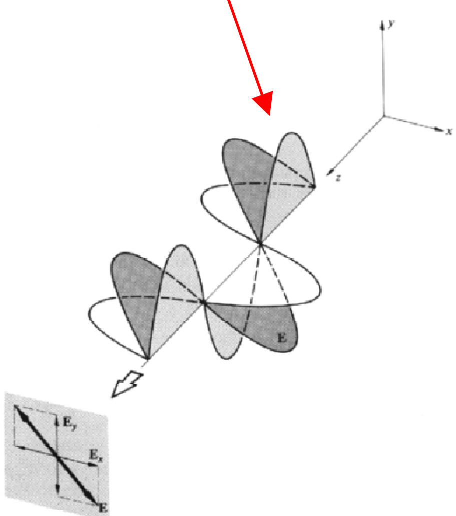
- PMD basics
- PMD impairments
- Passive PMD mitigation techniques
- Electrical equalization for PMD mitigation
- Optical PMD compensation
- Multi-channel PMDC for WDM systems

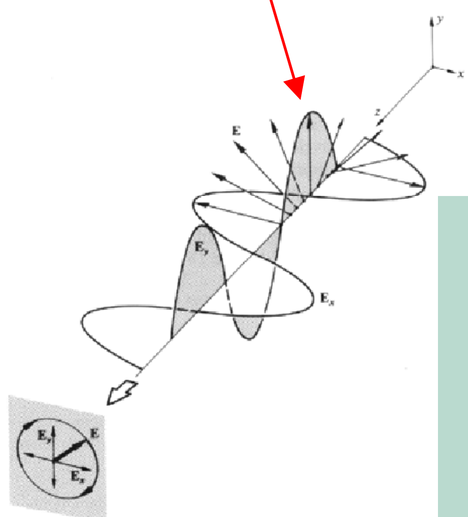
State of Polarization

The polarization state of a wave describes how the electrical field oscillates.

Linear SOP for in-phase field components

Circular or elliptical SOP for arbitray phase between field components



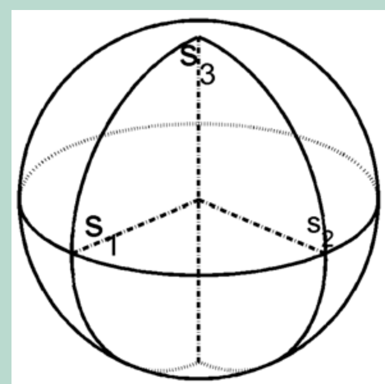


Jones vector

$$\vec{E} = \left[A_x e^{j\phi/2} \quad A_y e^{-j\phi/2} \right]^T$$

Stokes vector

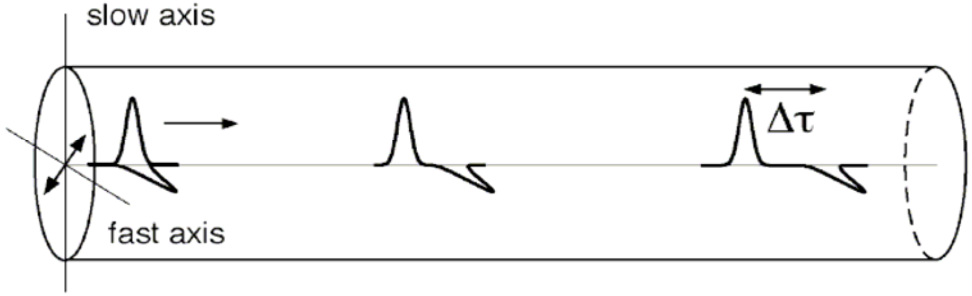
$$\vec{S} \equiv \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} A_x^2 + A_y^2 \\ A_x^2 - A_y^2 \\ 2A_x A_y \cos\phi \\ 2A_x A_y \sin\phi \end{bmatrix}$$



Poincaré sphere

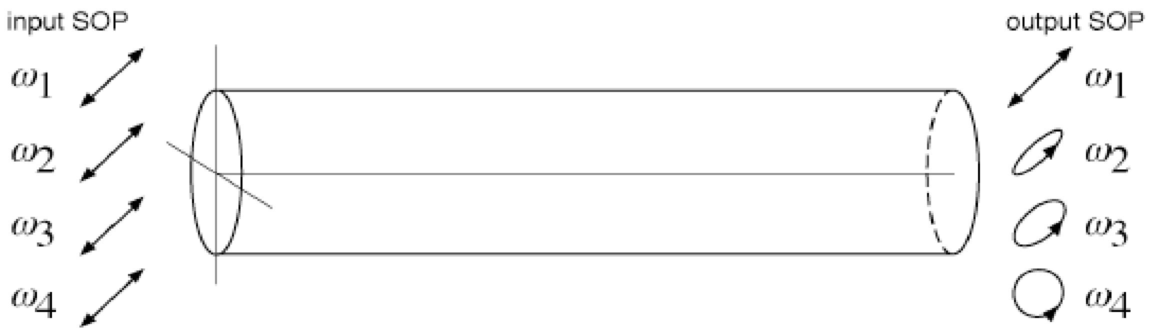
Birefringence —1st-order PMD

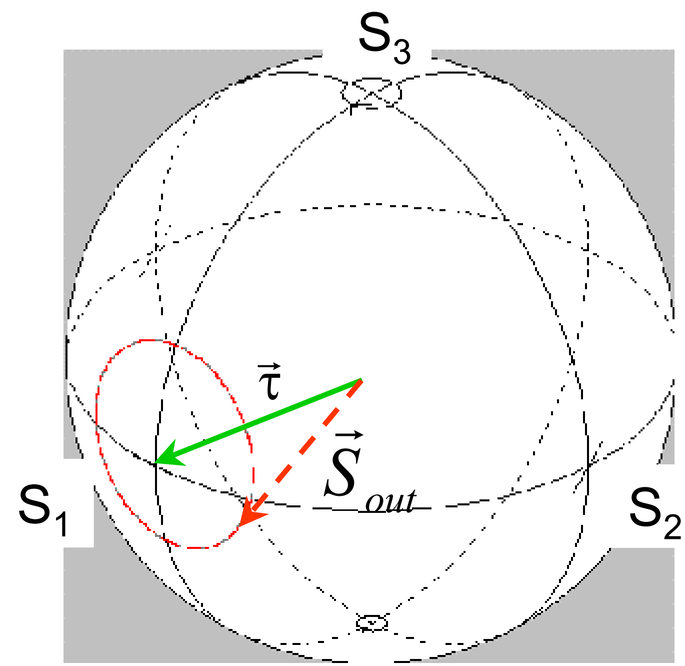
Time domain manifestation



DGD ~ L

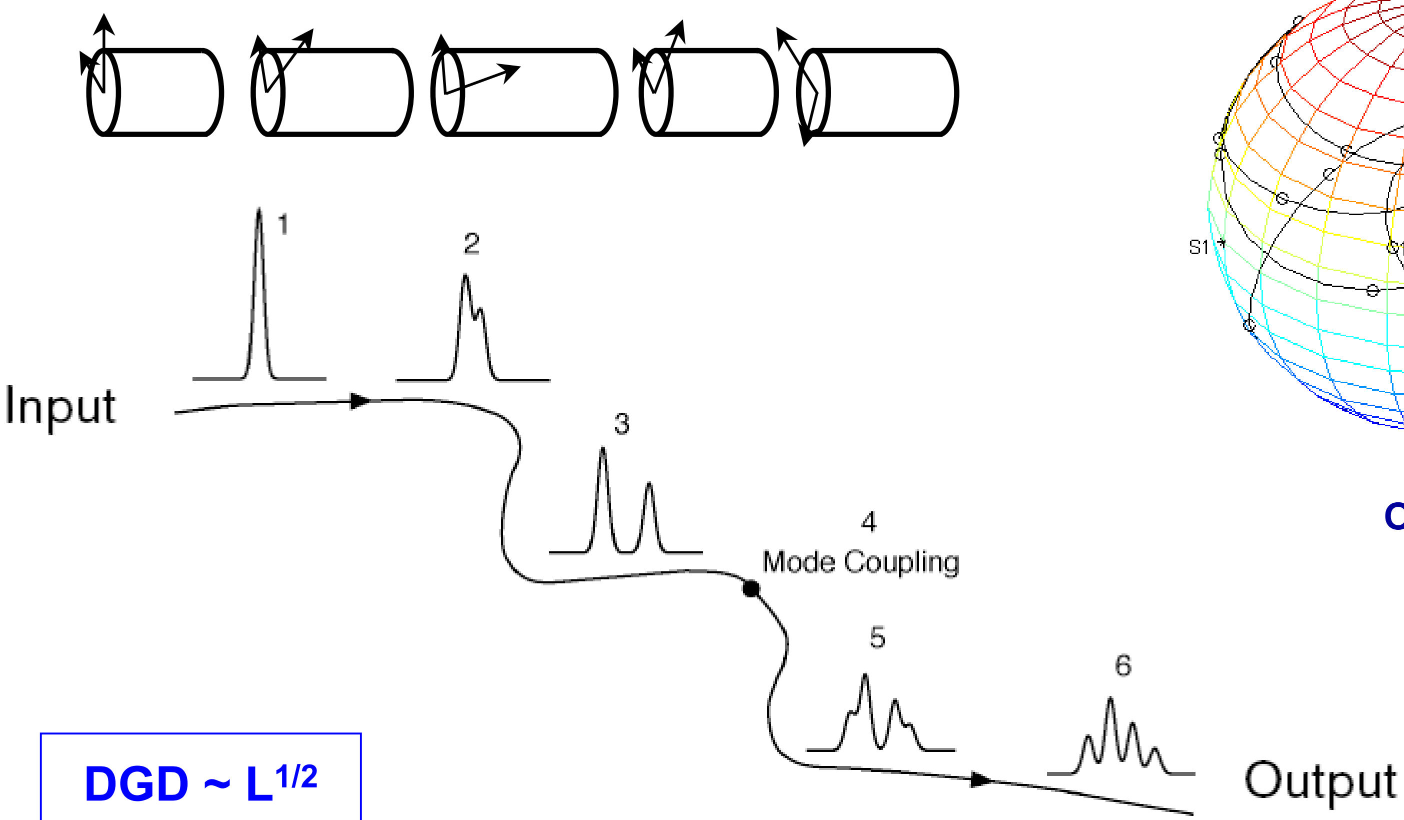
Frequency domain manifestation

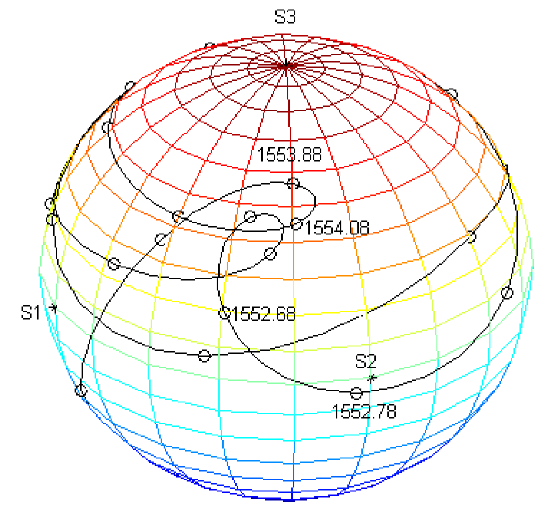




Random Birefringence in Fibers—All-Order PMD

Concatenation of random birefringent sections





Output SOP

DGD ~ $L^{1/2}$

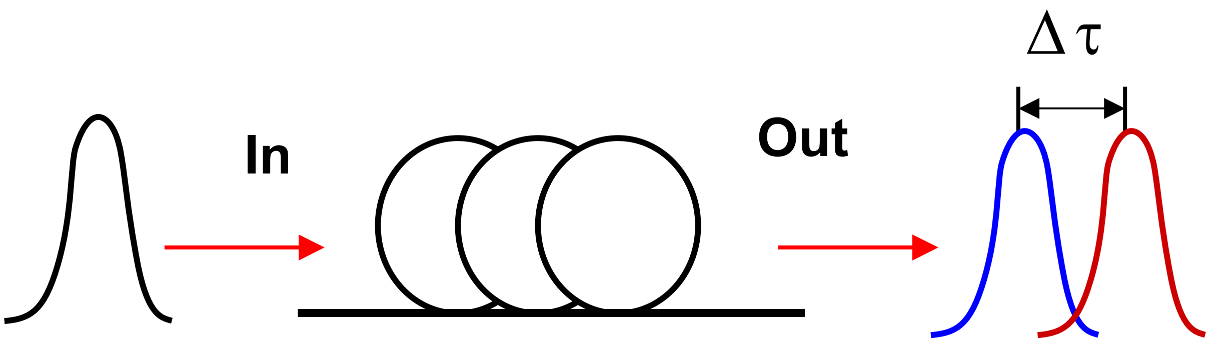
Principal States of Polarization (PSP)

Two special polarization states at the fiber input:
Output pulse is not distorted to 1st-order

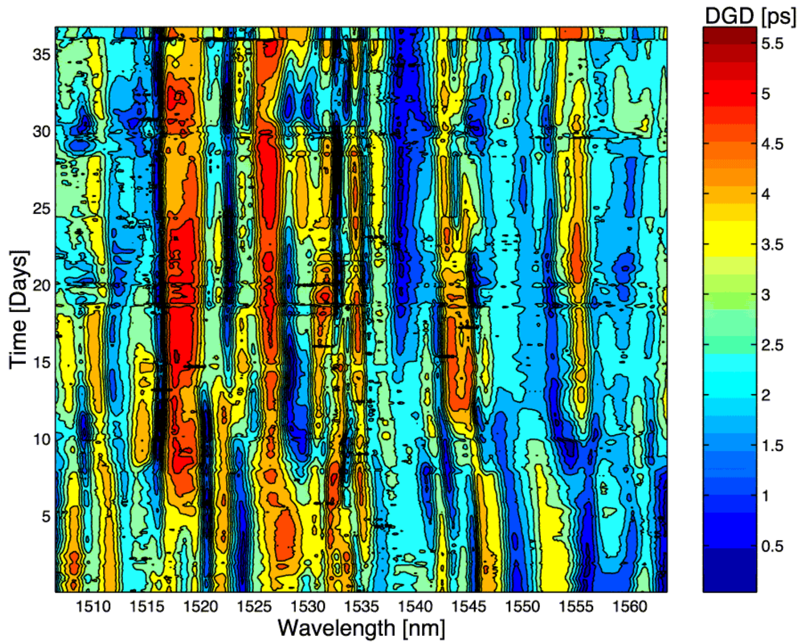
$$\begin{cases} - \textit{Slow PSP}: \quad |\, p\rangle\,;\, delay = \tau_0 + \frac{1}{2}\Delta\tau \\ - \textit{Fast PSP}: \quad |\, p_-\rangle\,;\, delay = \tau_0 - \frac{1}{2}\Delta\tau \end{cases}$$

Differential group delay (DGD): DGD = $\Delta\tau$

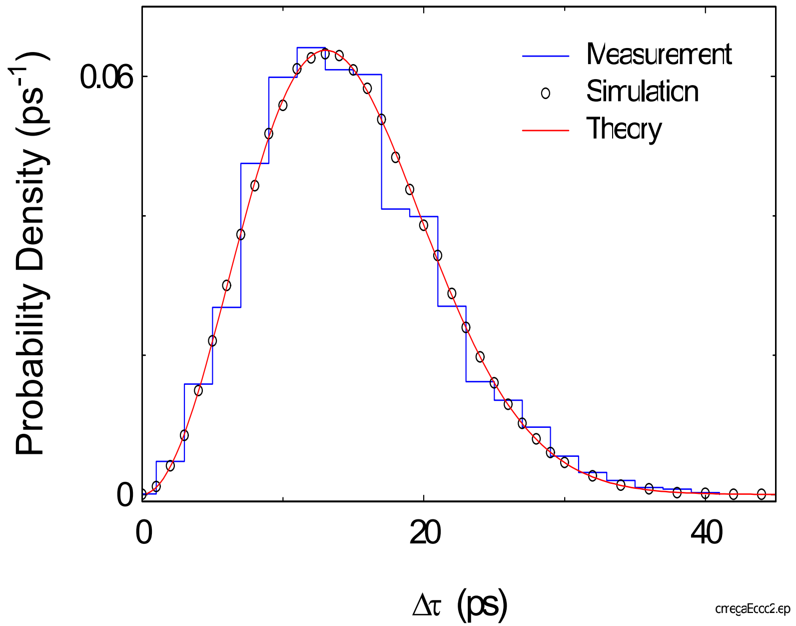
PMD vector: $\vec{\tau} = \Delta\tau\, \hat{p}$



PMD Drift and Variation



M. Karlsson et. al., JLT, vol 18, p. 941, 2000



DGD has Maxwellian distribution

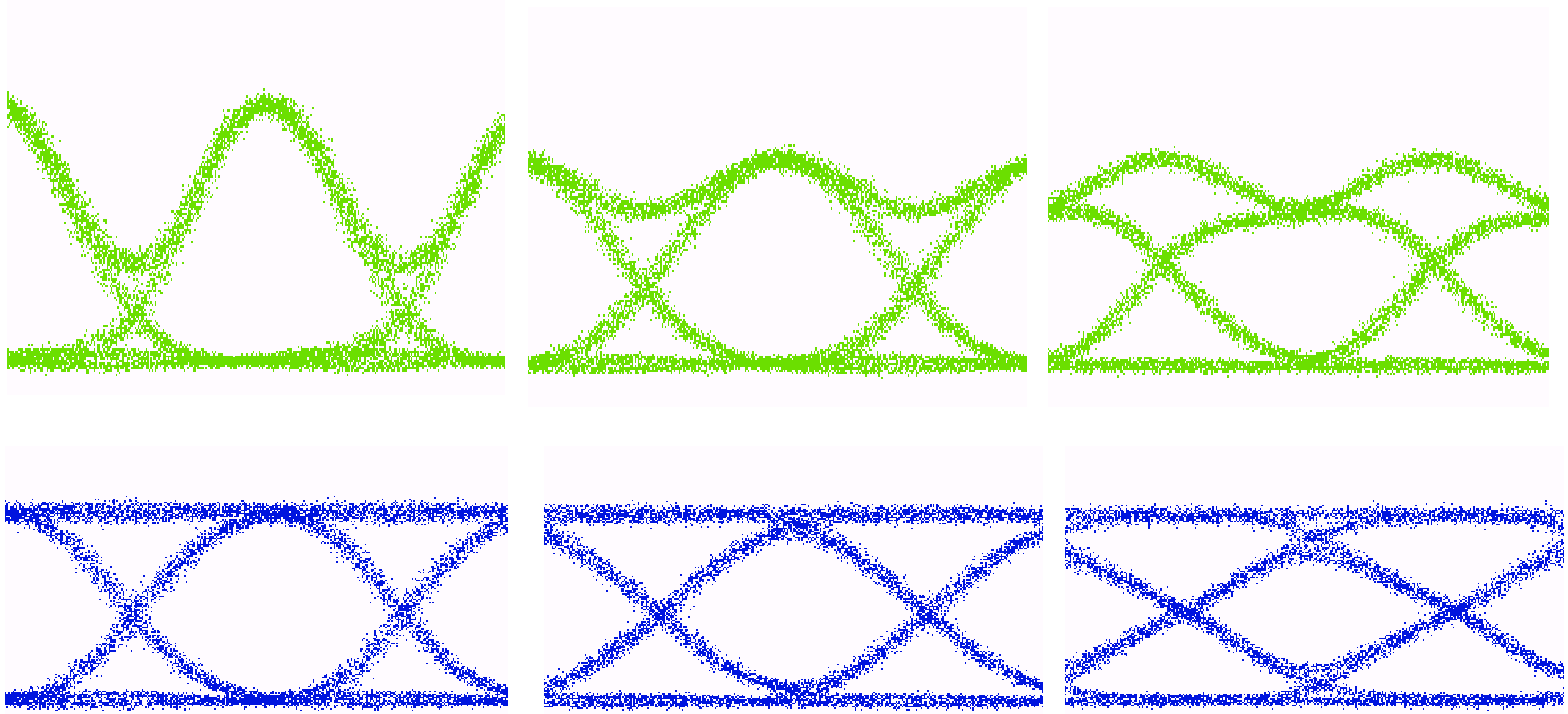
H. Kogelnik et. al., OFC'02, WD

- **PMD varies with wavelength and drifts with time**
- **Drift speed was observed to have a large range**
  - **Hours and days for buried fibers and undersea cables**
  - **millisecond or faster for aerial fibers and fibers under bridges**

- PMD basics
- **PMD impairments**
- Passive PMD mitigation techniques
- Electrical equalization for PMD mitigation
- Optical PMD compensation
- Multi-channel PMDC for WDM systems

PMD Induced Eye-Diagram Degradation

PMD induced pulse splitting and broadening causes ISI, which will degrade system performance.



RZ

NRZ

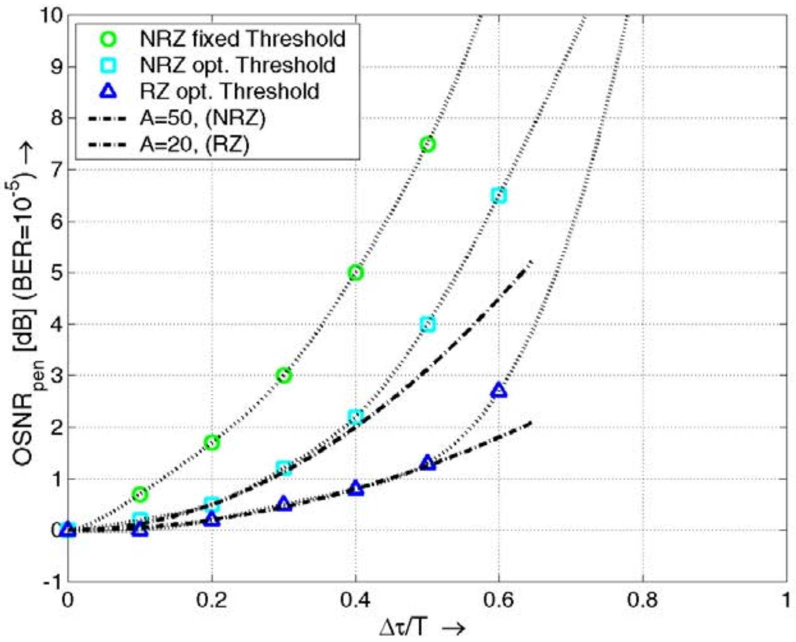
0 ps **40 ps** **60 ps**

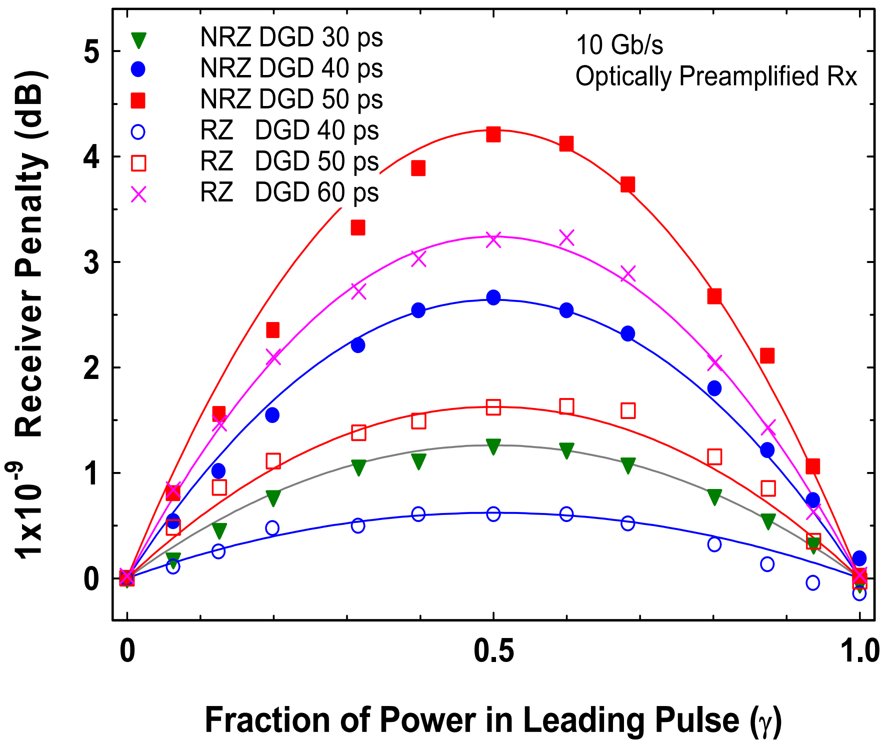
Eye-diagram degradation of 10 Gb/s RZ and NRZ signals caused by 1st –order PMD in worst case

System Penalty due to 1st-order PMD

For penalty less than 2 dB, 1st-order PMD can be approximated as

$\varepsilon\,(\text{dB}) \approx A\,(\Delta\tau / 2T)^2 \sin^2\Theta$ (*C. D. Poole et al., IEEE PTL., vol. 3, p. 68,1991.*)

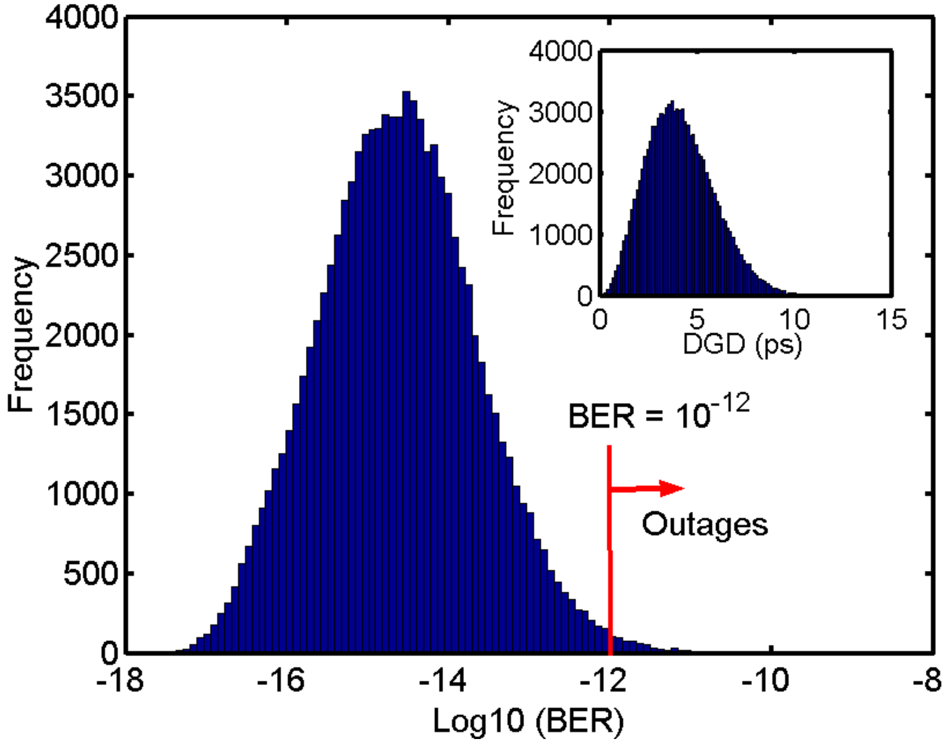




C.H.Kim et al, OFC 2002, TuI4

Outage Probabilities Induced by PMD

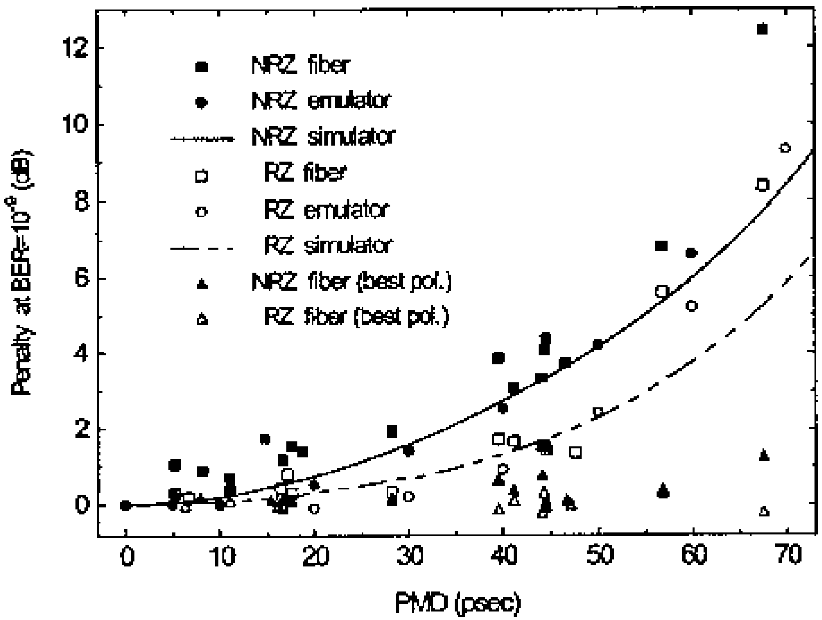
- **For any given system margin , there is a certain probability that the PMD induced penalty exceeds the margin, the probability is called outage probability**
- **Acceptable outage probabilities range between 10^{-4} to 10^{-8}**



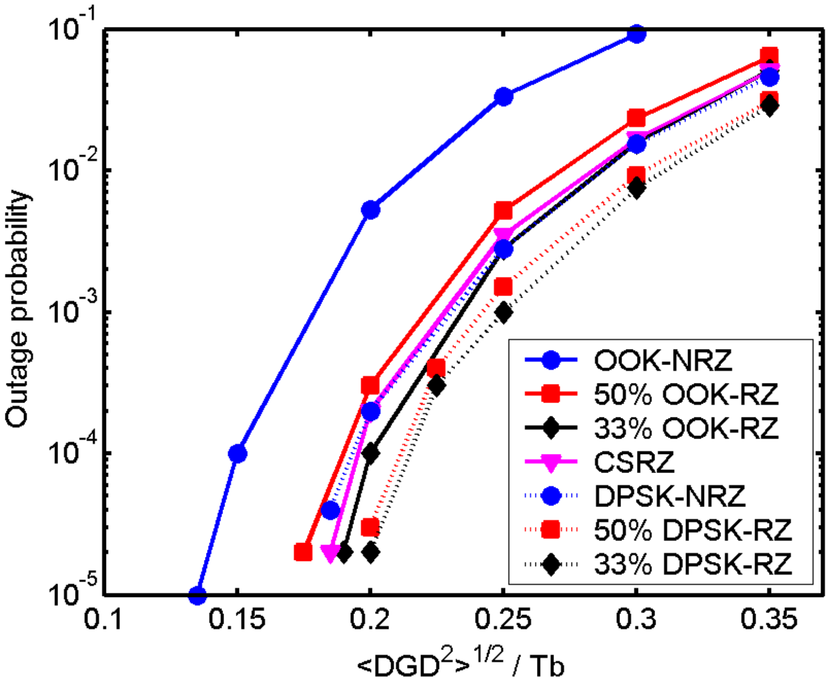
C. Xie, WOCC'2005

- PMD basics
- PMD impairments
- **Passive PMD mitigation techniques**
  - **Refer to the techniques that do not require dynamic adjustment**
- Electrical equalization for PMD mitigation
- Optical PMD compensation
- Multi-channel PMDC for WDM systems

Using PMD Robust Modulation Formats



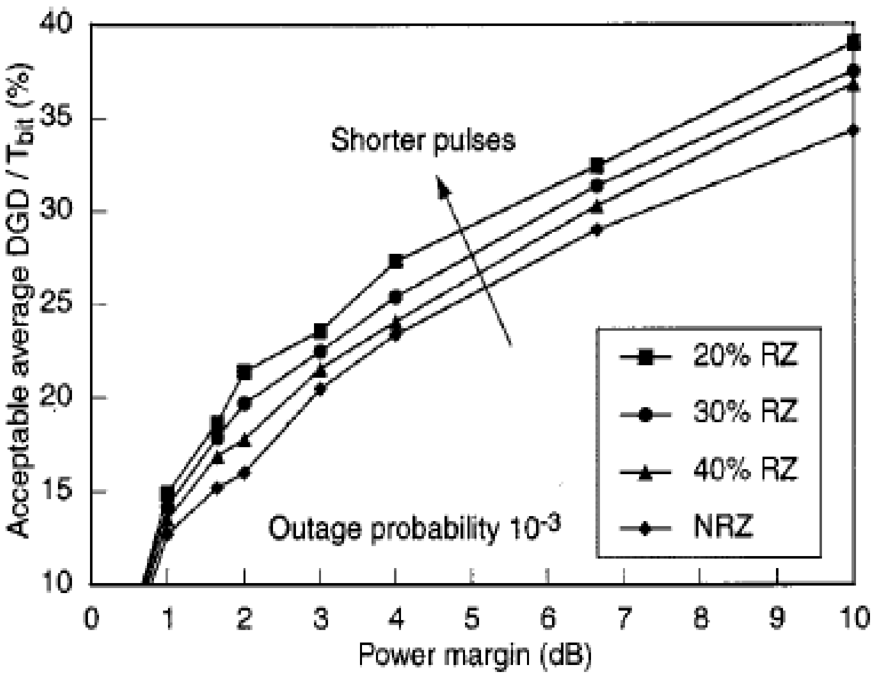
- *R. M. Jopson et al,OFC'1999, paper WE3.*



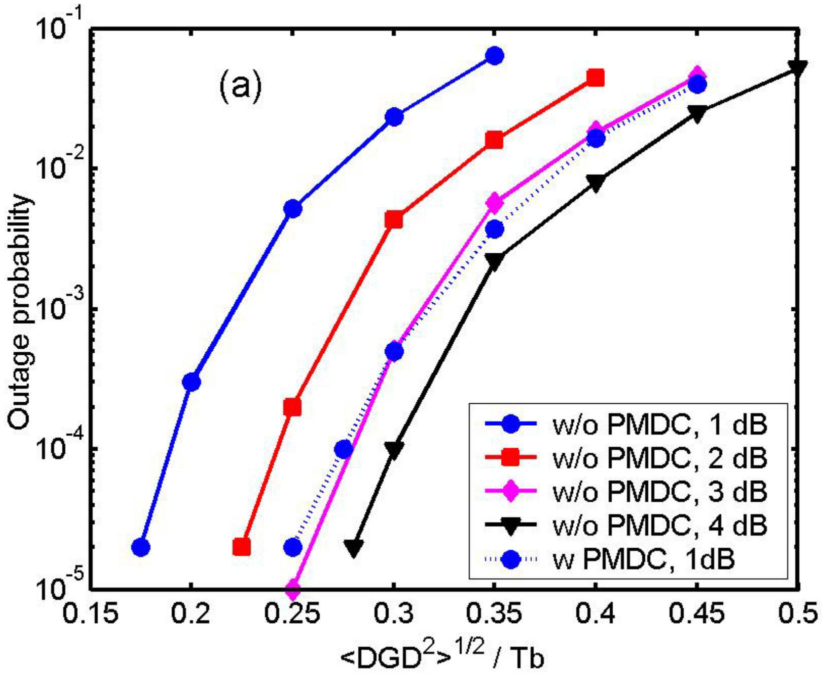
1 dB margin, BER = 10^{-12}

- *C. Xie et al, OFC'2003, paper TuO1*

Allocating More Margin to PMD

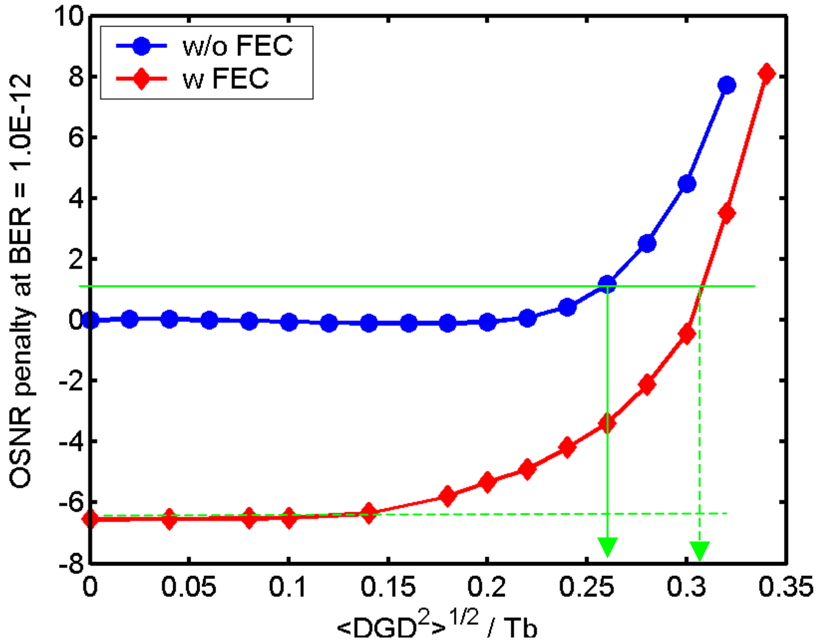


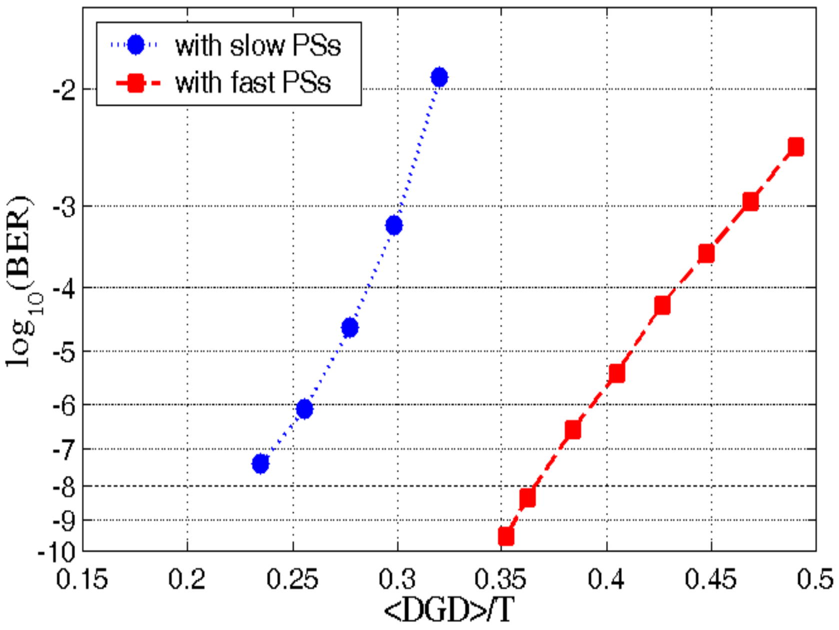
H. Sunnerud et al, IEEE PTL, vol. 13, p. 448, 2001



C. Xie et al, IEEE PTL, vol. 15, pp. 614, 2003.

Using FEC and Polarization Scrambling





FEC alone or FEC with PS at Tx cannot efficiently mitigate PMD

FEC together with fast distributed PS can effectively reduce PMD effects

• ***X. Liu, et al, ECOC'04, PD paper***

- PMD basics
- PMD impairments
- Passive PMD mitigation techniques
- **Electrical equalization for PMD mitigation**
- Optical PMD compensation
- Multi-channel PMDC for WDM systems

Electrical Equalizers for PMD Compensation

Electrical equalization advantages

- ❑ **Low cost**
- ❑ **Small size**
- ❑ **Simultaneous mitigation of various ISI independent of its origin**

but not so effective due to…

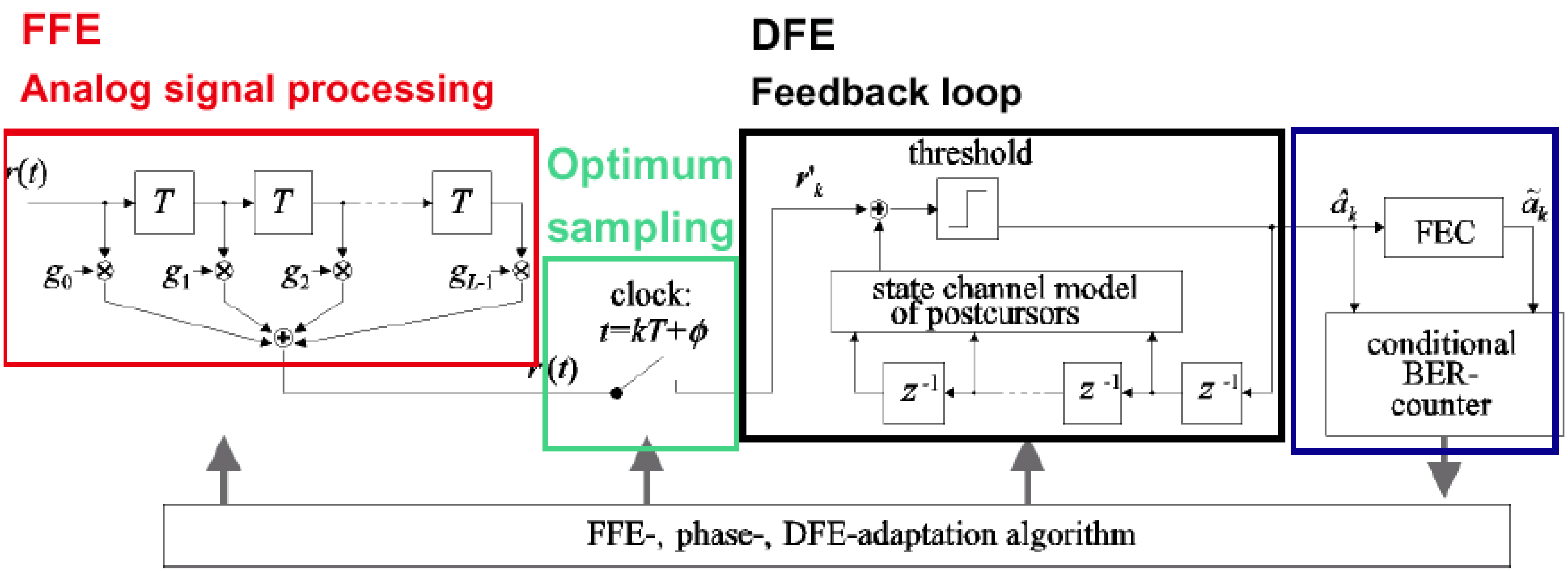
- ☐ **Lack of polarization information after detection**
- ☐ **Non-linear channel model**
- ☐ **Signal dependent noise**
- ☐ **High-speed signal processing**

Well-known concepts:

- ➢ **Transversal filter (FFE)**
- ➢ **Decision feed-back loop (DFE)**
- ➢ **Maximum Likelihood Sequence Estimation (MLSE)**

Structure of Electrical Equalizer

Architecture of 10 Gb/s ISI mitigator with FFE and DFE



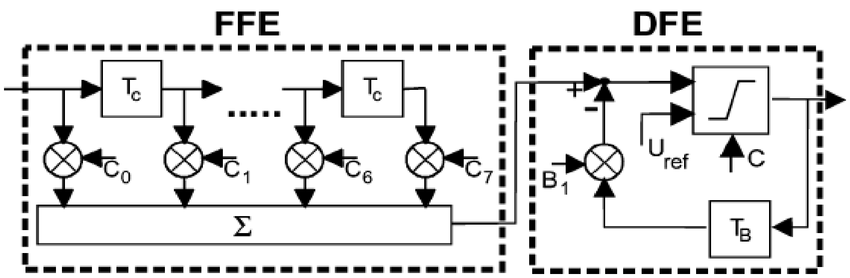
Adaptation based on conditional error counters from FEC decoder

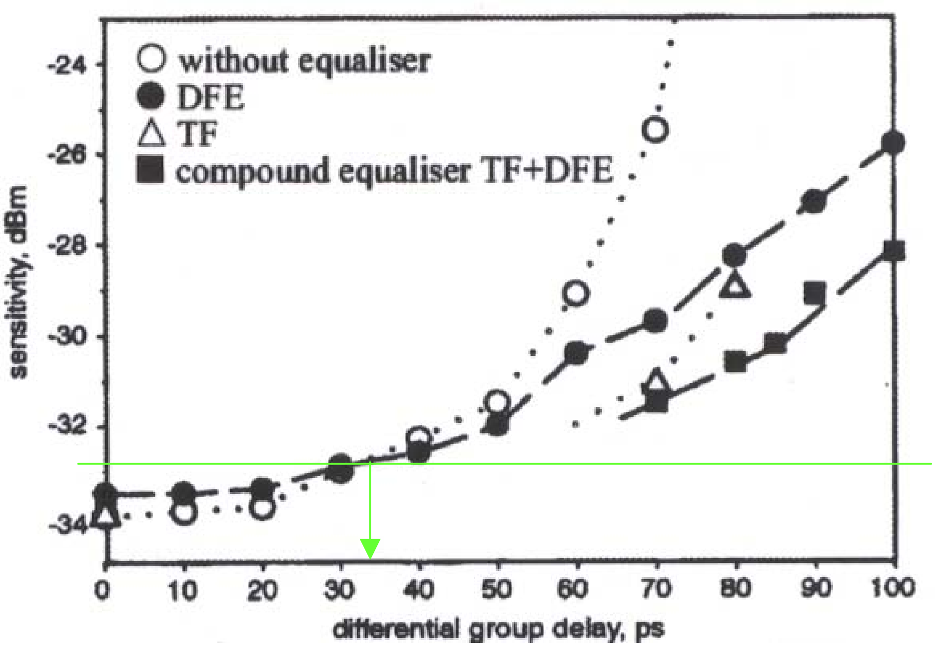
A. Dittrich et al, OFC'03, paper ThG5

Effectiveness of FFE and DFE

PMD penalty for an optically pre-amplified 10 Gb/s receiver with 1-tap DFE and 8-tap FFE (transversal filter)

More effective in high penalty range





H. Bülow et al., Electron. Lett., vol. 36, p. 163, 2000.

Electrical Equalizer @ 40Gb/s

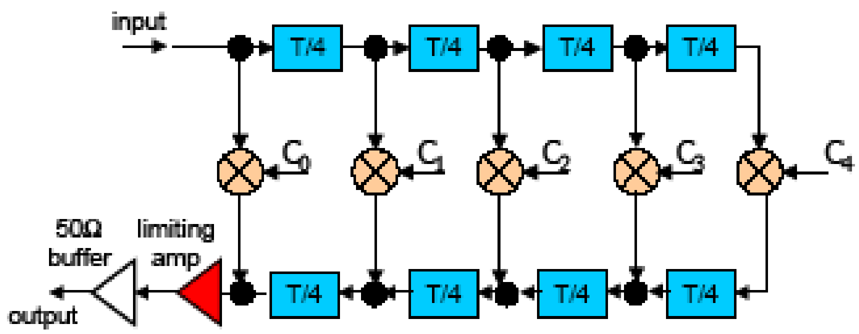


Fig.1 5 Tap Transversal Filter-based Equalizer

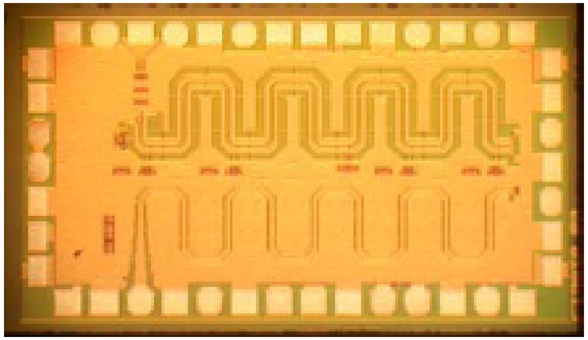


Fig.2 SiGe 40Gbit/s Equalizer IC Microphotograph

- 4(8) tap feed forward / T/2-spaced analog equalizer
- No absolute Q value given
- Increases DGD tolerance from 8ps to 12ps

(likely for optical duobinary)

H. Jiang et al, OFC'05, paper OWO2.

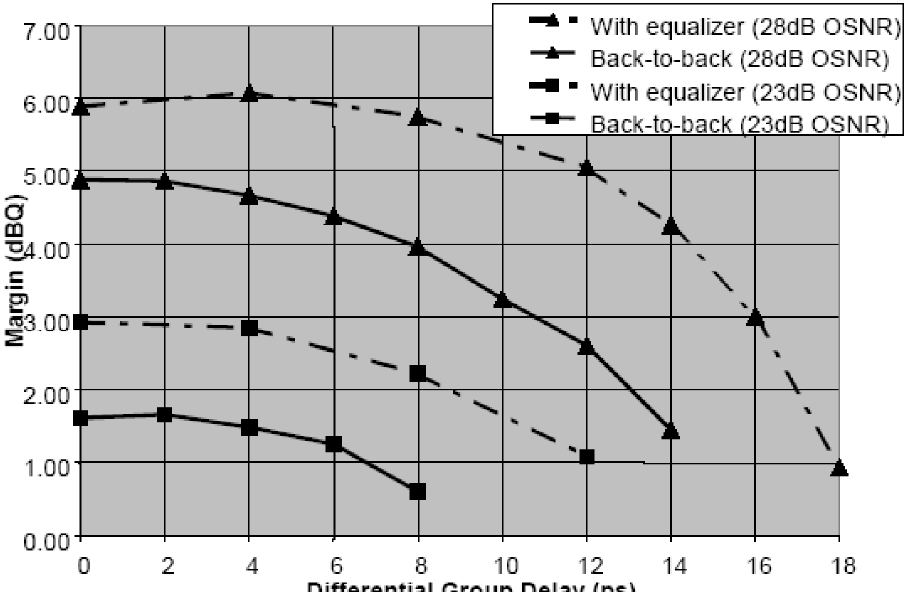


Fig.4 Polarization Mode Dispersion Sensitivity

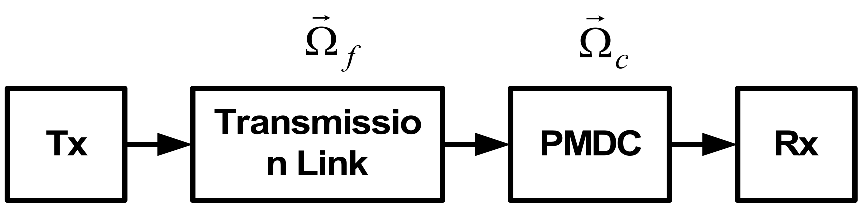
- PMD basics
- PMD impairments
- Passive PMD mitigation techniques
- Electrical equalization for PMD mitigation
- **Optical PMD compensation**
- Multi-channel PMDC for WDM systems

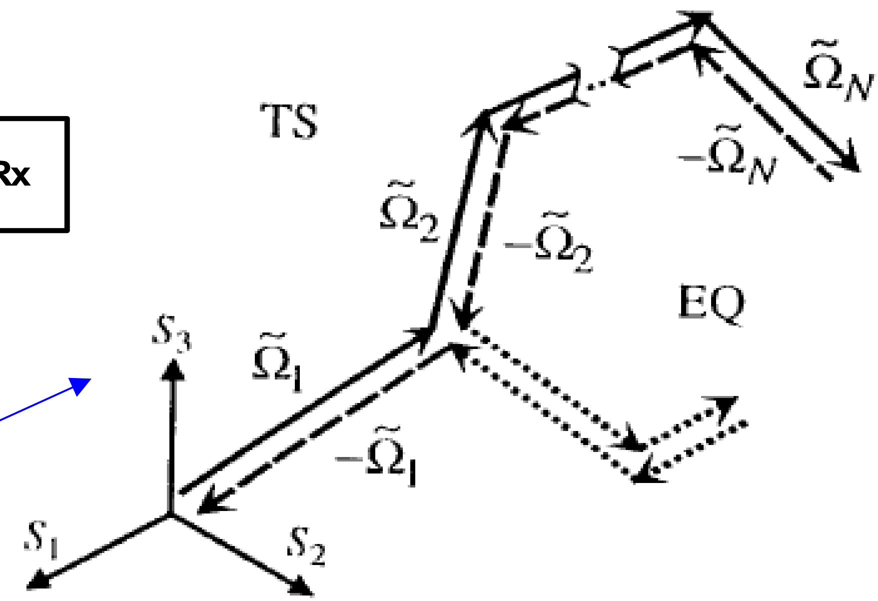
Concept of Optical PMDC

The aim of optical PMDC is to construct a PMD vector that is opposite to the PMD vector of the link

Due to existence of higher order PMD, this cannot be achieved over a wide bandwidth

In principle, more stage PMDC can achieve better performance

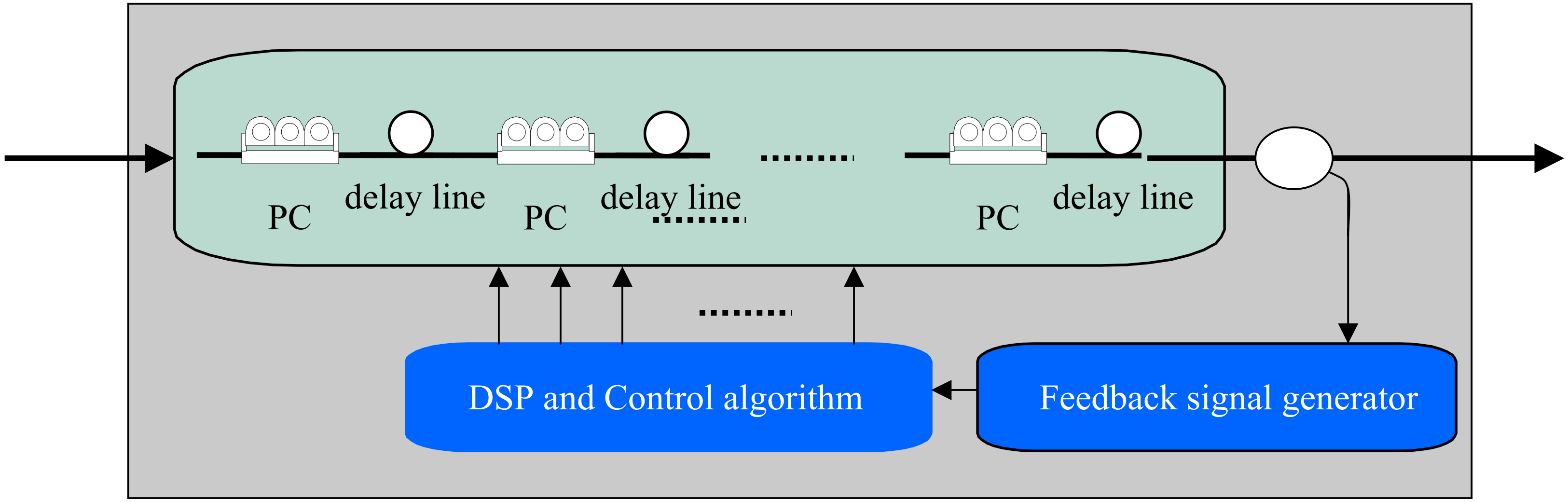




PMD profile of transmission span (solid) and perfect optical PMDC (dashed, dotted)

R. Noé et al., JLT, vol. 17, p. 1602, 1999.

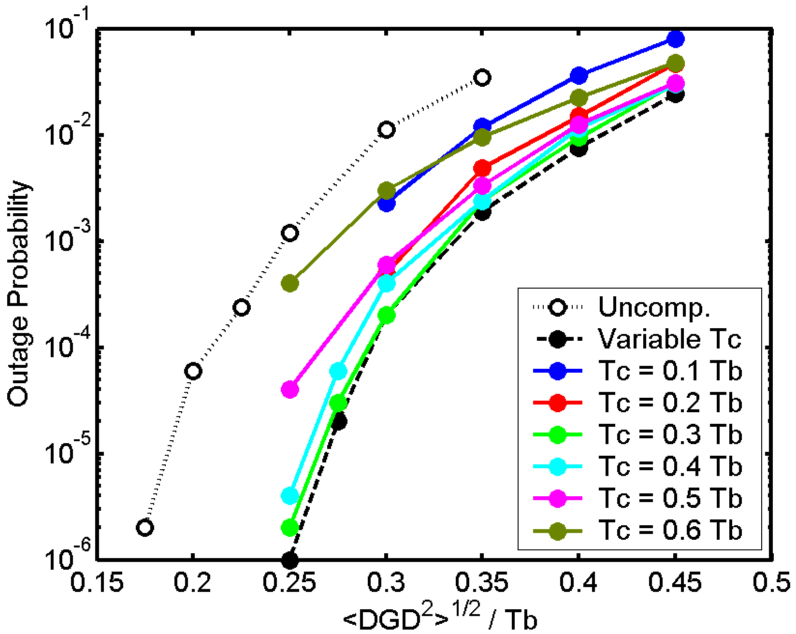
Structure of Optical PMDC



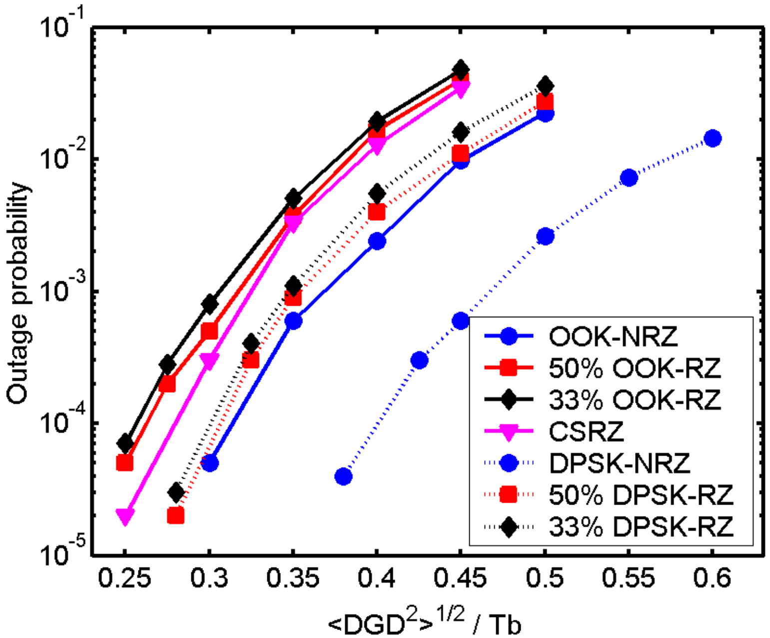
- **Compensation elements**
  - **one or many stages, fixed or variable delay lines**
- **Feedback signals**
  - **DOP, RF spectrum, eye-monitoring, Q factor**

  Summary see: ***J. Poirrier et al, OFC'02, WI3, C. Xie et al, IEEE PTL, vol. 17, p. 570, 2005.***
- **Control algorithms**
  - **Dithering method, or more efficient searching methods**

Performance of One-Stage Optical PMDC



One-stage PMDC with fixed delay line

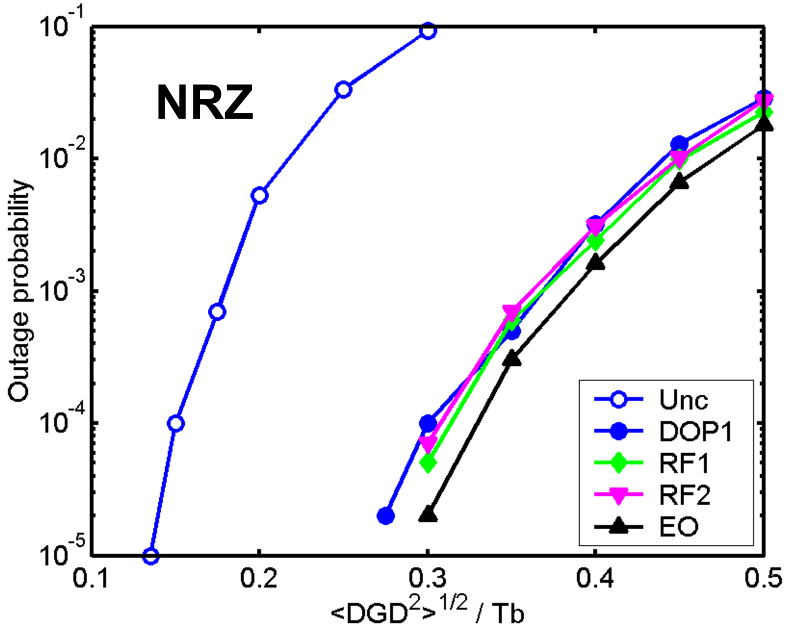


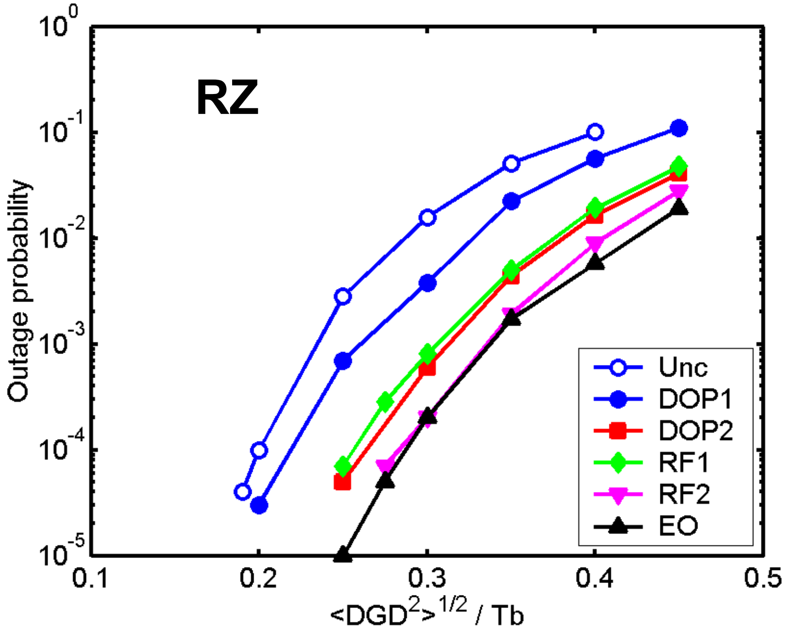
One-stage PMDC with variable delay line

1 dB margin, BER = 10^{-12}, RF spectrum signal as feedback control

- *C. Xie et al, IEEE PTL, vol. 15, p.1228, 2003.*
- *C. Xie et al, IEEE PTL, vol. 15, p.1168, 2003*

Effects of Feedback Signals on PMDC





1 dB margin, BER = 10^{-12}

DOP1: without filter

DOP2: with 0.8R optical filter

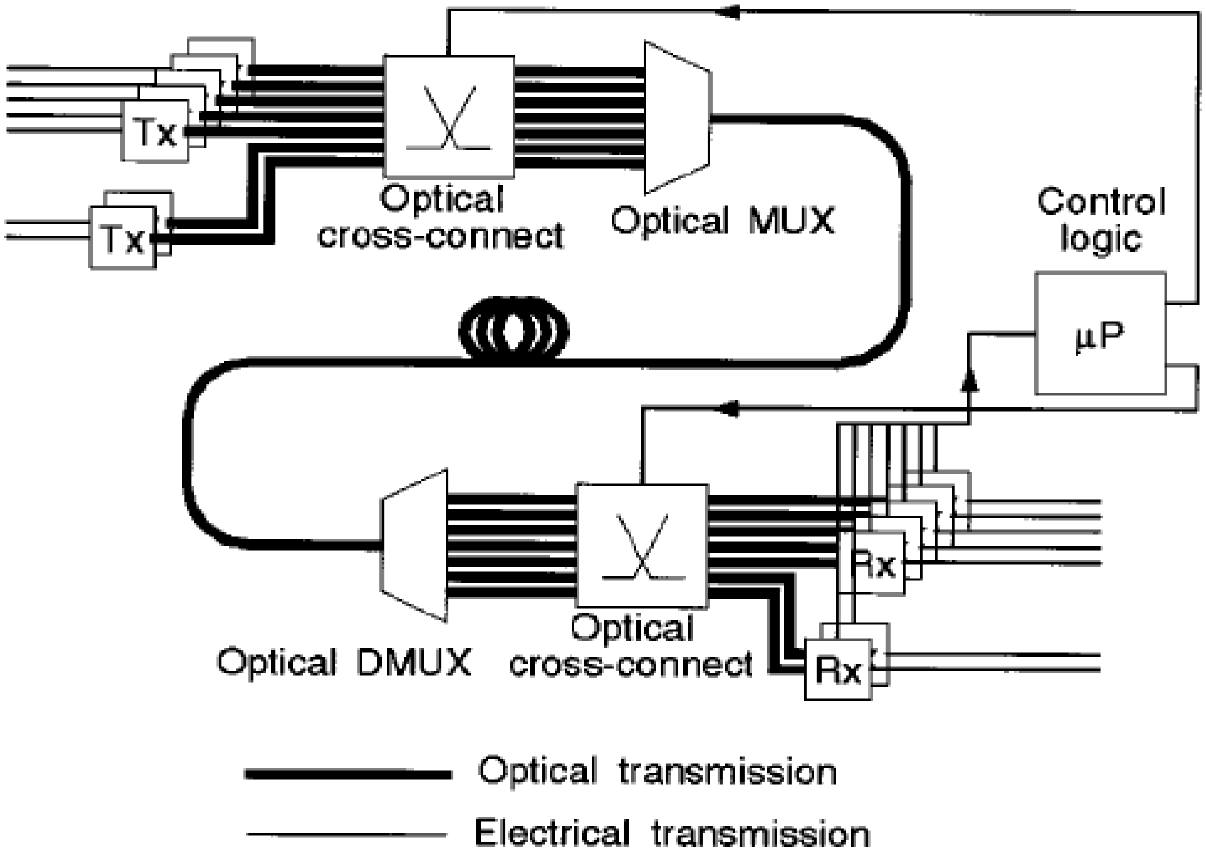
RF1: weighted RF power

RF2: 0.5R RF tone

C. Xie et al., OFC'04, paper WE4

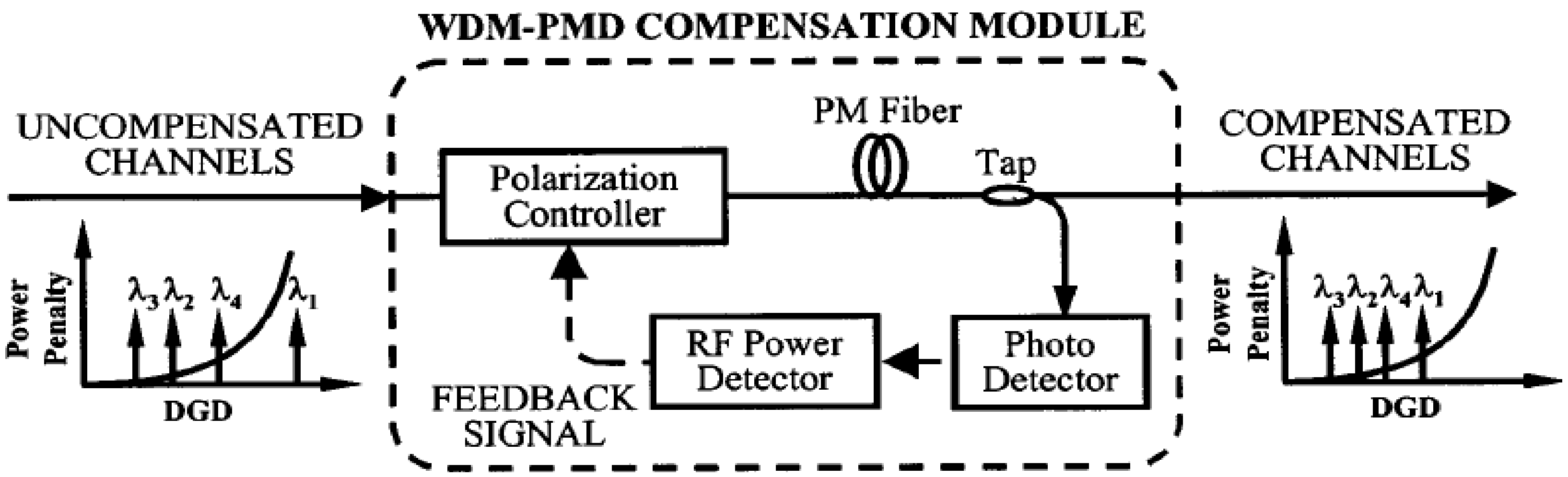
- PMD basics
- PMD impairments
- Passive PMD mitigation techniques
- Electrical equalization for PMD mitigation
- Optical PMD compensation
- **Multi-channel PMDC for WDM systems**
  - **To reduce system cost**

Channel Switching to Mitigate PMD Effects



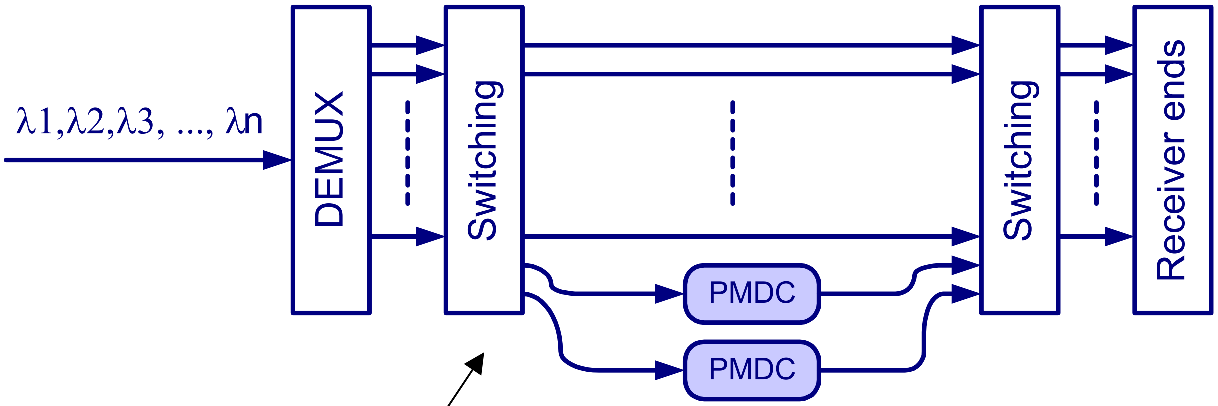
S. Särkimukka et al., JLT, vol. 20, p.368, 2002

Multi-Channel PMDC

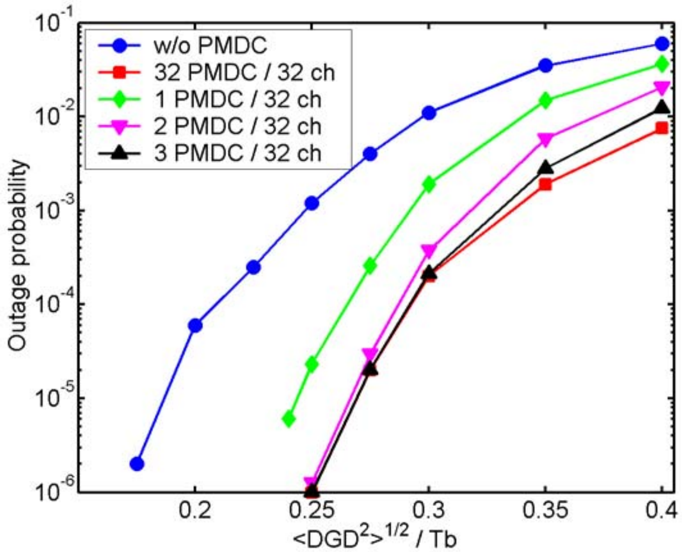


R. Khosravani et al., IEEE PTL, vol. 13, pp. 1370, 2001

Multi-channel Shared PMDC for WDM Systems



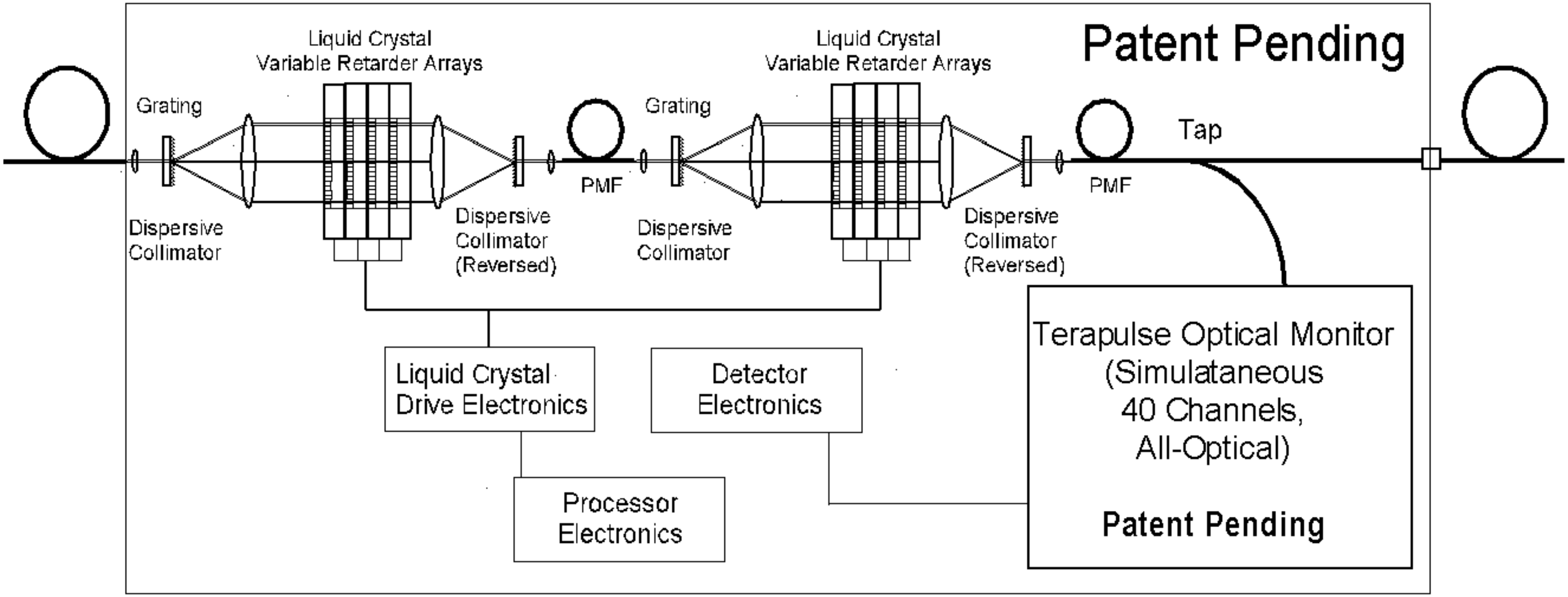
Scheme of multi-channel shared PMDC



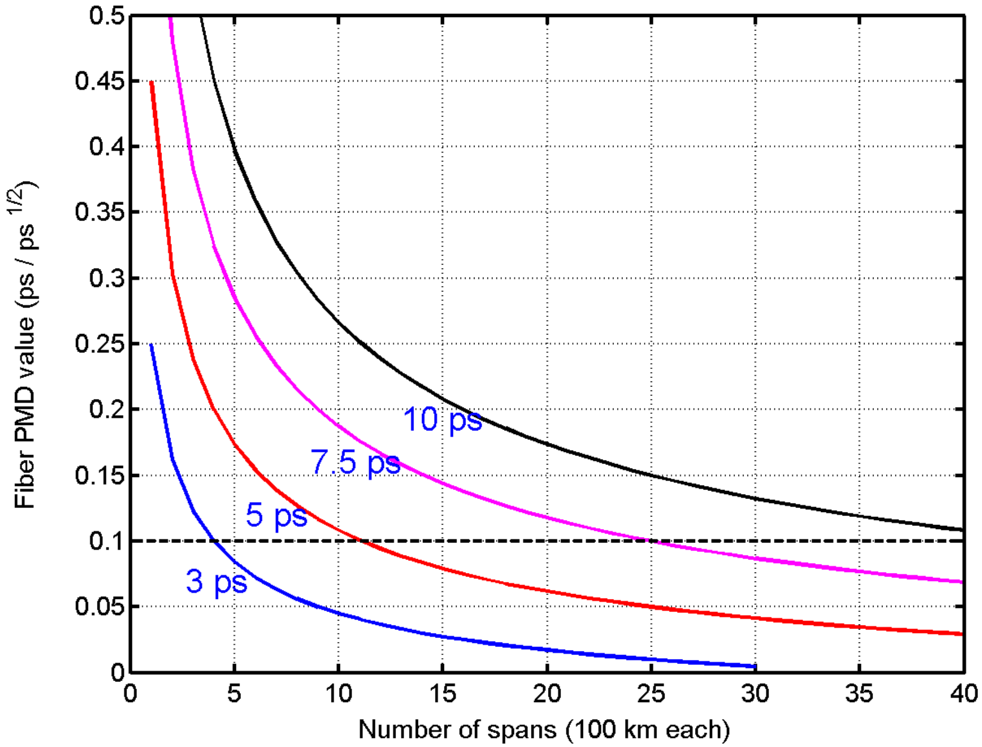
Performance of the shared PMDC

C. Xie et al., OFC'03, paper TuO6

Terapulse Multi-Channel PMDC



PMD Limited Distances for 40 Gb/s Systems



PMD limited transmission distances for systems with different PMD tolerances.

Assume component PMD of 0.5 ps per 100 km span.

The values in the figure are average tolerable PMD

Summary

- Due to its stochastic nature, PMD is considered to be one of the main obstacles to the deployment of optical communication systems with bit rates of 40 Gb/s and higher.
- Many PMD mitigation techniques have been developed and demonstrated in the past decade, some of them can significantly increase the system tolerance to PMD.
- Finding cost effective PMDC solutions requires deep understanding of PMD and customer needs.
- Currently no PMD compensation technique can eliminate PMD effects. In systems with large PMD, signal regeneration has to be used or the high PMD fibers have to be replaced with low PMD fibers (such as spun fibers).