Polarization Mode Dispersion

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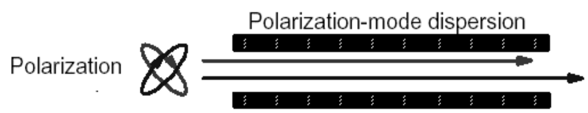
Outline

I. Introduction
II. Background Knowledge
   - Jones Matrix
   - Stokes Parameters
   - Poincare Sphere
III. PMD Measurement
IV. PMD Compensation
V. PMD Limitation
VI. Conclusion
VII. Reference

I. Introduction

- Polarization-mode dispersion (PMD) is one of several mechanisms (ex. Chromatic Dispersion) that broaden the signal pulses traveling in single mode fiber and consequently limit capacity and data rate.



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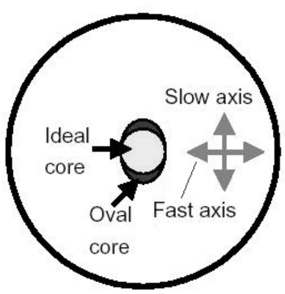
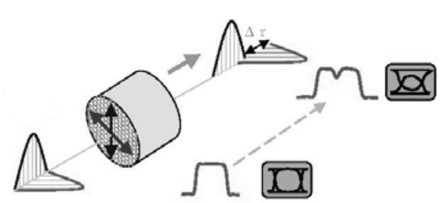
Introduction- Basic Concept(1/2)





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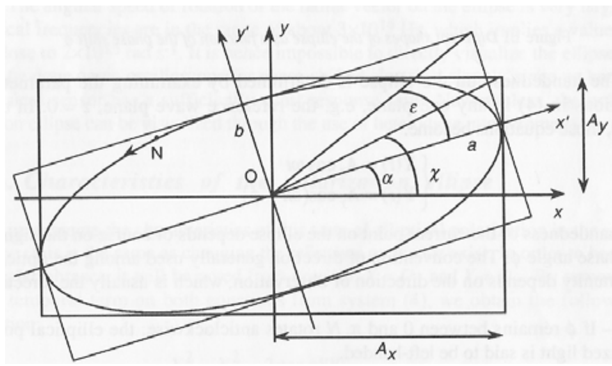
Introduction- Basic Concept(2/2)

➢ Elliptical Polarization



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Knowledge- Jones Matrix(1/2)

- A State of Polarization can be described by a two column vector V called Jones vector.

$$\mathbf{V} = \begin{bmatrix} A_x e^{i\phi_x} \\ A_y e^{i\phi_y} \end{bmatrix}$$

After normalized,

$$\mathbf{X} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad \mathbf{L} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ +i \end{bmatrix} \qquad \mathbf{J}(\chi, \varphi) = \begin{bmatrix} \cos\chi \\ \sin\chi e^{i\varphi} \end{bmatrix}$$

Linear *Circular* *Elliptical*

Knowledge- Jones Matrix(2/2)

- Using two orthogonal eigenvector **V**1 and **V**2 associated to two eigenvalues λ1 and λ2, we can specify a matrix M for modification of SOP in optical devices.

$$\mathbf{V}_1 = \begin{bmatrix} u \\ v \end{bmatrix} \qquad \mathbf{V}_2 = \begin{bmatrix} -v^* \\ u^* \end{bmatrix}$$

$$\mathbf{M} = \begin{bmatrix} \lambda_1 uu^* + \lambda_2 vv^* & (\lambda_1 - \lambda_2) uv^* \\ (\lambda_1 - \lambda_2) vu^* & \lambda_2 uu^* + \lambda_1 vv^* \end{bmatrix}$$

Note: Here, the eigenvectors are normalized.

Knowledge- Stokes Parameter(1/2)

- Introduce the P0,P1,P2 and P3 values defined by the following relations:

$$\begin{cases} P_0 = A_x^2 + A_y^2 \\ P_1 = A_x^2 - A_y^2 \\ P_2 = 2A_xA_y\cos\phi \\ P3 = 2A_xA_y\sin\phi \end{cases}$$

$$\begin{cases} P_0 = A_x^2 + A_y^2 \\ P_1 = A_x^2 - A_y^2 \\ P_2 = 2A_xA_y\cos\phi \\ P3 = 2A_xA_y\sin\phi \end{cases}$$

$$\begin{cases} I_{+45^\circ} - I_{-45^\circ} = 2A_xA_y\cos\phi \\ I_L - I_R = 2A_xA_y\sin\phi \end{cases}$$

- Also, with the help of **V** states split on the basis at $\pm 45^\circ$ and the two circular states we have the right formula.

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Knowledge- Stokes Parameter(2/2)

- Using two formulas above and $S_{0,1,2,3} = P_{0,1,2,3}/P_0$ and conventions brought in about the angles:

$$\begin{cases} P_0 = I_x + I_y \\ P_1 = I_x - I_y \\ P_2 = I_{+45^\circ} - I_{-45^\circ} \\ P3 = I_L - I_R \end{cases}$$

$$\begin{cases} S_1 = \cos 2\varepsilon \cos 2\alpha = \cos 2\chi \\ S_2 = \cos 2\varepsilon \sin 2\alpha = \sin 2\chi \cos\phi \\ S_3 = \sin 2\varepsilon \qquad = \pm \sin 2\chi \sin\phi \end{cases}$$

- These three S parameters suggest a spherical representation of the State of Polarization

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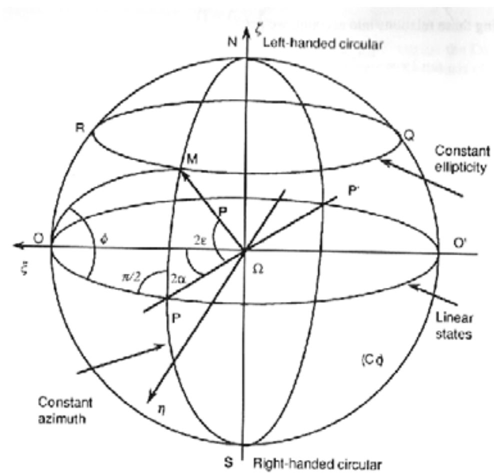
Knowledge- Poincare Sphere

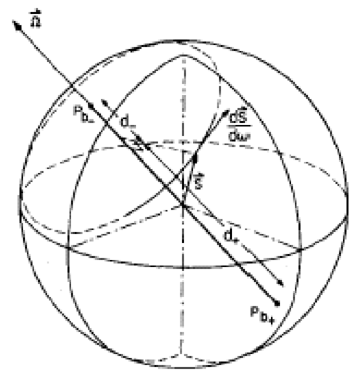


Knowledge- First Order PMD(1/3)

- First Order PMD is under the assumption that the output Principle States remain the same with the change of frequency. This first order effects of polarization dispersion may arise from a differential time of traveling delay associated the two principle states.

Knowledge- First Order PMD(2/3)

- Under the assumption above, as the $\Delta\varphi$ changes with frequency, the stokes vector representing the output SOP will rotate about the vector describing output principle state with rate exactly equal to the rate of change of $\Delta\varphi$



P_b : output principle state, d: distances from the plane to P_b

Knowledge- First Order PMD(3/3)

- We express the first order frequency dependence of the output Stokes vector:

$$\frac{d\vec{S}}{d\omega} = \vec{\Omega} \times \hat{S}$$

(where Ω is the rate and direction of rotation)

$$\vec{\Omega} = \frac{d\Delta\phi}{d\omega}\hat{P}_b \qquad \Delta\tau = \frac{d\Delta\phi}{d\omega}\text{[1]}$$

$$\Rightarrow \vec{\Omega} = \Delta\tau \cdot \hat{P}_b \qquad |\vec{\Omega}| = \Delta\tau$$

Note: rotation Stokes vector is independent of input state of polarization

Knowledge- Second Order PMD

- In fact, $\vec{\Omega}(\omega)$ is a function of frequency. The second order PMD can be characterized as:

$$\vec{\Omega}(\omega) = \Delta\tau_{\omega}\vec{q} + \Delta\tau\vec{q}_{w}$$

where the subscript ω denotes differentiation.

$\Delta\tau_{\omega}$ is known to cause polarization dependent chromatic dispersion.

q_{ω} describes depolarization, i.e. a change in the direction of the PSP

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III. PMD Measurement

Measurement Method

A. Poincare Sphere Method
B. Jones Matrix Method
C. Wavelength Scanning Method

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Measurement- Method(1/3)

- Poincare Sphere Method

  The Poincare sphere method measures PMD in the frequency domain by measuring the SOP at the output of a fiber as a function of frequency with fixed input polarization. By differentiating the data with respect to frequency with at least two input polarization, one can use formulas discussed above to determine the vector Ω and thus the differential delay Δτ.

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Measurement- Method(2/3)

- Jones Matrix Method

  Jones matrix method uses a set of predetermined launch polarization states to determine the complex Jones Matrix of the fiber at each frequency. One can compute the frequency derivative and from this the differential group delay using

$$\Delta\tau = 2\sqrt{|u'|^2 + |v'|^2}$$

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Measurement- Method(3/3)

- Wavelength Scanning Method

  In this method, light with fixed polarization is transmitted through DUT and then a polarizer placed at the output. The normalized transmission through the polarizer is measured as a function of wavelength. The transmission spectrum shows a series of peaks and valleys as a result of variation of the polarization incident on the polarizer. (See a simple derivation.)

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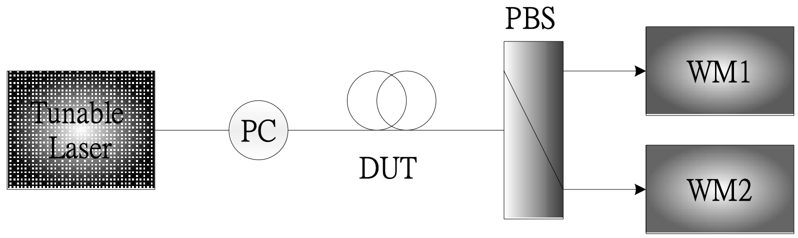
Measurement- Experiment I (1/2)

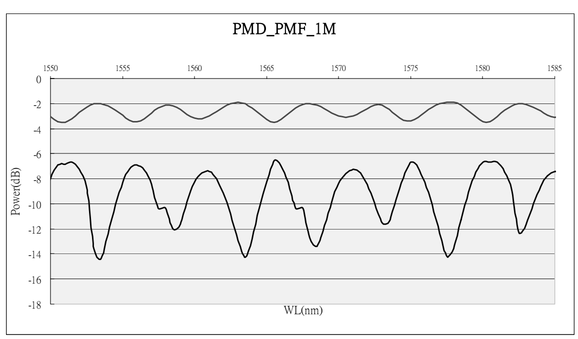
- Experiment I Setup (using wavelength scanning)



DUT: Device Under Test (Here, PM Fiber~1m)

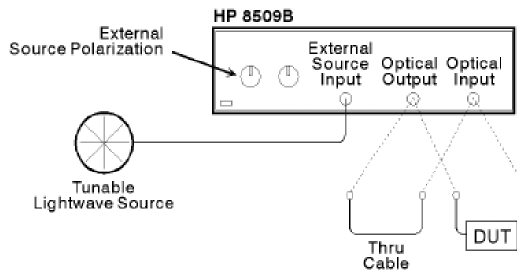
Measurement- Experiment I (2/2)

- Experiment I Result (with DGD~52.96 ps/rtkm)



Measurement- Experiment II (1/3)

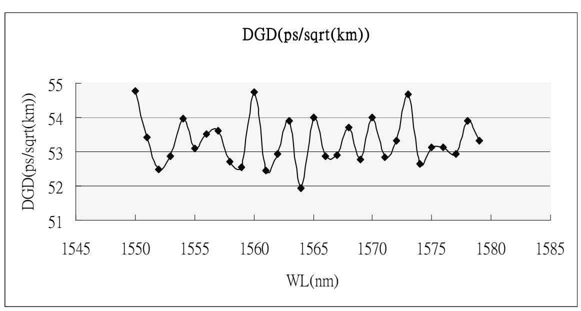
- Experiment II Setup (Analyzer HP8509B)



Note :HP 8509B supplies two methods: Jones Matrix Method and Wavelength Scanning.

Measurement- Experiment II (2/3)

- Experiment II Result A(JME method DGD~53.303 ps/rtkm)



Measurement- Experiment II (3/3)

- Experiment II Result B (Wavelength scanning method DGD~43.5422 ps/rtkm)

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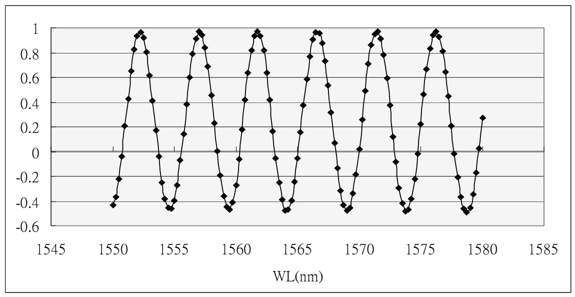

Measurement- Comparison

- Experiment I (WS) DGD~52.96 ps/rtkm
- Experiment II (JME) DGD~53.303 ps/rtkm
- Experiment II (WS) DGD~43.5422 ps/rtkm

				PMD (ps)			
Fiber	Type	Length (meters)	N_e/N_m	Mean Level	Extrema	HP8509B (Wavelength)	HP8509B (Temp.)
1	SM	3810	1.3	1.3±0.15	1.0±0.09	1.1	1.3
2	SM	8362	1.7	4.7±0.4	5.3±0.3	5.1	5.2
3	SM	7636	1.6	7.5±0.5	7.9±0.4	8.1	7.7
4	PM	1.0	0.97	1.56	1.52	1.54	—

DGD~48.067 ps/rtkm

It shows that our measurement is very close to the paper[2].

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IV. PMD Compensation

PMD Compensation Method

- PSP Method
- Feedback Method
- Electronics Method (such as using LiNbO3, predistortion method)

The main feedback signals are the DOP, a measure of the electrical spectral width, or an estimation of the bit-error rate through eye monitoring.

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PMDC- PSP Method (1/2)

- Using the fact that light launched in a PSP doesn't change polarization at the output to first order in ω, one may avoid change in SOP if the input is launched in one of the PSPs.

$$S_{out} = T(\omega) S_{in}$$

$$S_{out} = T(\omega + \Delta\omega) S_{in}$$

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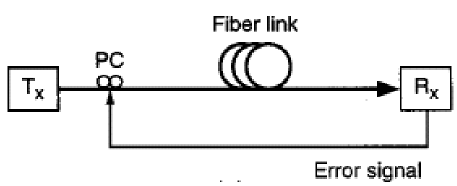
PMDC- PSP Method (2/2)



However, the main drawback of this method that a feedback signal must be transmitted all the way from receiver back to the transmitter.

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PMDC- Feedback Method (1/3)

- The most popular concepts of optical PMD compensation use a feedback loop comprising an equalizer and a detection part which adaptively optimize the parameter of equalizer to compensate the PMD effect.

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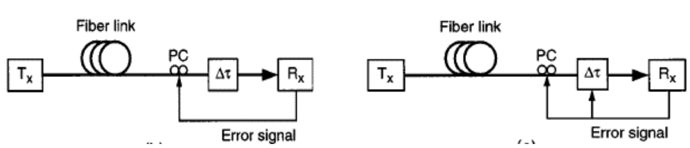
PMDC- Feedback Method (2/3)

- Two examples of postcompensators are shown. One is a PC and a variable delay. Another is a PC and a variable delay.



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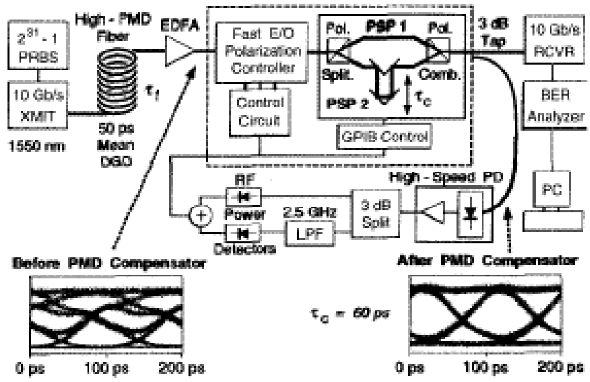
PMDC- Feedback Method (3/3)



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V. PMD Limitation

- Speed
- Cost
- PMD Compensator for Wideband
- Outage Probability

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PMD Limitation- Speed

- The speed requirements are still subject to research and not really answered yet. However, recent long-term measurement shows that in most systems PMD changes not faster in order of minutes.

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PMD Limitation- Cost

- Besides technical considerations the acceptance of PMD compensator in commercial systems is strongly influenced by the price of a single PMDC as the cost is multiplied by the number of channels in a WDM system. Nonetheless, alternatives to PMD compensation such as "installing better fibers" or "inserting an OEO regenerator along the link" seem to be more expensive.

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PMD Limitation- Wideband Com.

- Although the common post-compensation method is quite promising for both low-penalty operation and simple receiver configuration, it operates mostly on a single channel. In order to lower down the cost and have wideband PMD compensator, new method needs to be figured out.

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VI. Conclusion

- The complex answer to "How much PMD can be compensated by a PMDC" still raises a hurdle to the deployment of PMDC. Also, the overall performance of a PMDC strongly depends on the Tx/Rx design and the modulation format. Thus, it's probably more realistic to see the PMDC as a part of the receiver.
- However, optical PMDC unfolds its advantages in extending the reach of PMD-limited transmission systems when operating at bit rates of 40G and above

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VII. Reference

[1]C. D Poole, "Phenomenological approach to polarization mode dispersion in long single mode fiber." 1986

[2]C. D Poole, "Polarization Mode Dispersion Measurement Based on Transmission Spectra Through a Polarizer." 1994

[3]R. Khosravani, "Polarization Mode Dispersion Compensation in WDM systems" 2001

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