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Polarization mode dispersion measurement using polarization phase shift method for passive optical components

（日本語訳題名：偏波位相シフト法による光受動部品の偏波モード分散測定方法）

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Polarization mode dispersion measurement using polarization phase shift method for passive optical components

（偏波位相シフト法による光受動部品の偏波モード分散測定方法）

1 Scope

The purpose of this measurement procedure is to present a method to measure the polarization mode dispersion (PMD) of passive optical components.

This procedure will cover measurements of both broadband, and dense wavelength division multiplexing (DWDM) components.

This procedure can be applied to laboratory, factory and field measurements of PMD in components.

This procedure can be applied to a transmissive or reflective device under test (DUT). In the latter case, the DUT connection is via a coupler or circulator, which should have a known very low PMD value.

2 Normative references

IEC 61280-4-4: Polarization mode dispersion measurement for installed links

IEC 61282-y: Background to polarization mode dispersion measurements

IEC 61300-3-32: Polarization mode dispersion measurement for passive optical components

3 Apparatus

The primary technique of the polarization phase shift method is given. Figure 1 shows a block diagram of the polarization phase shift method.

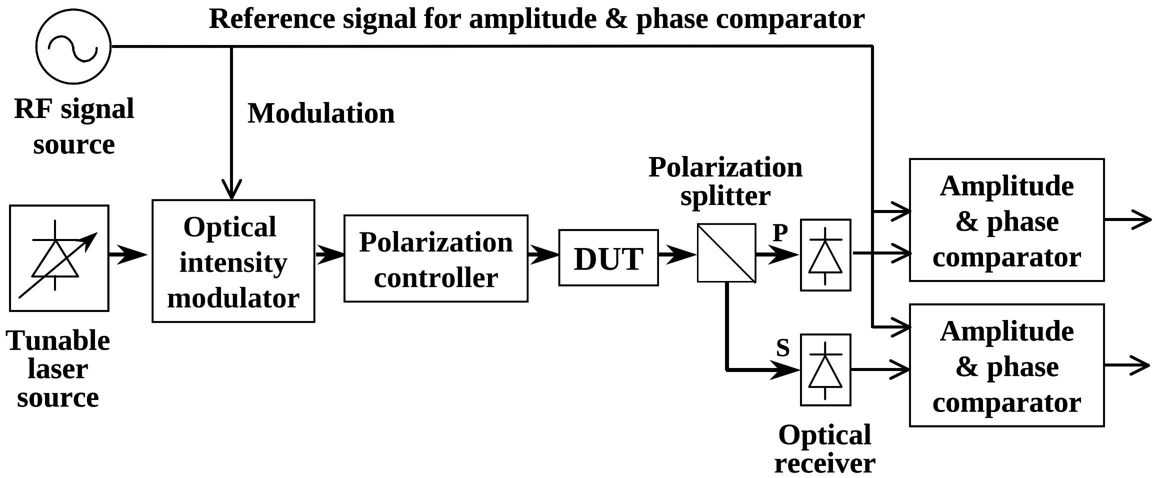

Figure 1 - Block diagram for polarization phase shift method

3.1 Tunable laser source

A tunable laser source is used as the light source. The tuning range of the laser shall be sufficient to cover the wavelength range for to be measured. The completely self-contained temperature controlled and current controlled external-cavity laser unit is generally employed. The output of a tunable laser source, with an output power of about 0dBm and a spectral width of less than 50MHz, is connected to an optical intensity modulator by a polarization maintaining fiber.

3.2 Modulation

3.2.1 RF signal source

The RF signal source provides a modulating signal for the optical intensity modulator. Some of the modulating signal is sent to the amplitude and phase comparator as a reference signal. The RF signal source requires a broadband characteristic because it is necessary to provide a sinusoidal modulating signal whose frequency range is typically from 50 MHz to 3 GHz. In the selection of the modulation frequency undesirable influences of modulation sidebands and the DGD measurement resolution should be considered.

The sidebands are generated on both sides of the optical signal with a frequency difference of f, which is the modulation frequency. This represents the light spectrum spread. The effective wavelength resolution, $\Delta\lambda$ (nm), is restricted by the sideband, and is generally given as:

$$\Delta\lambda = 2 \cdot \frac{\lambda^2 \cdot f}{c} \tag{1}$$

Where

λ : wavelength (nm)

f : modulation frequency (GHz)

c : velocity of light in vacuum (m/s)

In addition, the DGD measurement resolution, ΔDGD (ps), is also restricted by the modulation frequency, f, and is typically given as:

$$\Delta DGD = \frac{\Delta\phi \cdot 10^3}{360 \cdot f} \tag{2}$$

Where

$\Delta\phi$: phase resolution of the phase comparator (degree)

f : modulation frequency (GHz)

The total phase accuracy including the frequency stability of the RF signal source is required to be +/-0.3 degree or less to ensure adequate measurement precision.

3.2.2 Optical intensity modulator

The optical intensity modulator receives modulating signals from the RF signal source, and modulates the intensity of output light from the tunable laser source. The insertion loss of the optical intensity modulator should be used less than 5dB. $LiNbO_3$ (LN) modulator, with an on-off extinction ratio of 20dB or more and a polarization extinction ratio of 20dB or more, shall be used. The optical performances such as insertion loss, on-off extinction ratio and polarization extinction ratio should be satisfied the required value over the wavelength range to be measured. A polarization maintaining fiber is used as an input fiber in order to connect with a tunable laser source. A drive voltage is generally determined from half-wavelength voltage ($V\pi$) of the LN modulator, and the output power of RF signal source is adjusted that the degree of optical intensity modulation will be about 20%.

3.3 Polarization controller

The polarization controller is used to deliver polarized light of specific SOPs to the DUT. The polarization controller consists of three components: a polarizer, a 1/4-wave plate, and a 1/2-wave plate. Rotating the set of two retardation plates can generate any polarization state. The polarization controller needs excellent characteristics to provide expected measurement precision. The angle adjustment resolution is required to be less than +/-0.1 degree. The insertion loss should be used less than 1dB and the polarization extinction ratio should be 30dB or more over the wavelength range to be measured.

3.4 Polarization splitter

The output from the DUT is coupled into a polarization splitter before the optical receivers. The polarization splitter separates the output from the DUT into two polarised waves, P- and S-polarised light. The polarization splitter consists of a non-isotropic crystal such as a calcite prism, and generally possesses a high polarization extinction ratio, such as 30dB or more. The insertion loss should be used less than 1dB. The optical performances such as polarization extinction ratio and insertion loss of the polarization splitter should be satisfied the required value over the wavelength range to be measured.

3.5 Optical receivers

The optical receivers convert the modulated light from the DUT into an electrical signal. A PIN photodiode, with a good linearity and a low noise density of about 10pA/rHz, is generally used. The PIN photodiode must have bandpass characteristics sufficient enough to respond to the modulation frequency of the RF signal source. In addition, to ensure a high S/N ratio, a broadband and low noise amplifier should be used in the stage after the optical receivers.

3.6 Amplitude and phase comparator

The amplitude and phase comparator measures amplitude and phase by comparing the signals for each polarised wave component with the reference signal from the RF signal source. The group delay, τ (ps), is calculated from the phase using the following expression:

$$\tau = \frac{\phi \cdot 10^3}{360 \cdot f} \tag{3}$$

Where

ϕ : phase (degree)

f : modulation frequency (GHz)

The reference signal, which is part of the modulating signal from the RF signal source, is provided to the amplitude and phase comparator. The reference signal shall be synchronised to the modulating signal.

4 Procedure

4.1 Modulation frequency

The choice of modulation frequency is based on the wavelength resolution, $\Delta\lambda$, required for the measurement results and the DGD measurement resolution, ΔDGD. For more information, refer to Section 3.2.1.

4.2 Wavelength increment

Two wavelengths are required to obtain a DGD value because the wavelength differentiation in this wavelength increment, $\delta\lambda$, is used when calculating a DGD. This wavelength increment, $\delta\lambda$, will be called wavelength step size and the procedure about the determination of $\delta\lambda$ is explained. When the wavelength of the tuneable laser source is changed $\delta\lambda$, $\delta\lambda=(\lambda+\delta\lambda)-\lambda$, it is made for polarization angle change of SOP outputted from the DUT to become less than 45 degrees. The $\delta\lambda$ (nm) is usually expressed as:

$$\delta\lambda \leq \frac{\lambda^2 \cdot 10^3}{4 \cdot c \cdot \Delta\tau_{max}} \quad (4)$$

where

λ : wavelength of the region measured (nm)

c : velocity of light in vacuum (m/s)

$\Delta\tau_{max}$: maximum DGD value of the DUT (ps)

For example, the product of maximum DGD value, $\Delta\tau_{max}$, and wavelength increment, $\delta\lambda$, shall remain less than 2 ps･nm at 1550nm.

4.3 Scanning wavelengths and measuring DGDs

The tuneable laser source is used to perform a wavelength sweep along the desired wavelength range, and the DGD value is calculated at each wavelength. In addition, the PMD value of the DUT can be calculated after an average DGD has been calculated based on the DGD values previously obtained along the measured wavelength range.

This method uses a pair of orthogonal polarised waves (the 0-degree and 90-degree linearly polarised waves). The 0-degree and 90-degree linearly polarised waves are launched into the DUT and the output is separated into two polarised wave components by the polarization splitter. After that, the amplitude and group delay for each of the polarised waves (the P- and S-polarised light) at a specific measurement wavelength are measured. That is, the P- and S-polarised light amplitudes ($|T_{11}|^2_{mea}$ and $|T_{21}|^2_{mea}$, respectively) and the group delays ($d\Phi_{11}/d\omega_{mea}$ and $d\Phi_{21}/d\omega_{mea}$, respectively) for the 0-degree linearly polarised wave are measured. And for the 90-degree linearly polarised wave, the P- and S-polarised light amplitudes ($|T_{12}|^2_{mea}$ and $|T_{22}|^2_{mea}$) and the group delays ($d\Phi_{12}/d\omega_{mea}$ and $d\Phi_{22}/d\omega_{mea}$) are measured.

4.4 Calibration

A calibration is performed on a low PMD single-mode fibre whose length is 1m or less before DUT measurement. First, adjust the 1/4- and 1/2-wave plates to generate the 0-degree linearly polarised wave that matches the P-polarised wave of the polarization splitter. Next, generate the 90-degree linearly polarised wave that matches the S-polarised wave of the polarization splitter. After that, at a specific measurement wavelength, measure the amplitude and group delay characteristics for each of two polarised waves (the P- and S-polarised light) that are separated by the polarization splitter while the 0-degree and 90-degree linearly polarised waves are alternately launched. That is, the P- and S-polarised light amplitudes ($|T_{11}|^2_{cal}$ and $|T_{21}|^2_{cal}$, respectively) and the group delays ($d\Phi_{11}/d\omega_{cal}$ and $d\Phi_{21}/d\omega_{cal}$, respectively) for the 0-degree linearly polarised wave are measured. And for the 90-degree linearly polarised wave, the P- and S-polarised light amplitudes ($|T_{12}|^2_{cal}$ and $|T_{22}|^2_{cal}$) and group delays ($d\Phi_{12}/d\omega_{cal}$ and $d\Phi_{22}/d\omega_{cal}$) are measured. The DGD value is calculated from the measured values using the expression described in Section 4.5.

4.5 DGD calculation

The following parameters are calculated using measured values in Section 4.3 and 4.4.

$$\bar{\alpha}_1 = \frac{\Delta\Theta}{\Delta\omega} = \frac{\Delta\Theta}{2\pi c \cdot \delta\lambda} \cdot \lambda_i \lambda_f$$
$$\bar{\beta}_1 = \frac{1}{4}\left(\frac{d\Phi_{11}}{d\omega} - \frac{d\Phi_{22}}{d\omega} - \frac{d\Phi_{21}}{d\omega} + \frac{d\Phi_{12}}{d\omega}\right)$$
$$\bar{\gamma}_1 = \frac{1}{4}\left(\frac{d\Phi_{11}}{d\omega} - \frac{d\Phi_{22}}{d\omega} + \frac{d\Phi_{21}}{d\omega} - \frac{d\Phi_{12}}{d\omega}\right) \qquad (5)$$
$$\Theta = \frac{1}{2}\cos^{-1}\left(\frac{|T_{11}|^2 - |T_{21}|^2}{|T_{11}|^2 + |T_{21}|^2}\right)$$
$$\cos 2\Theta_0 = \frac{|T_{11}|^2 - |T_{21}|^2}{|T_{11}|^2 + |T_{21}|^2}$$

where

λ_i, λ_f: the initial and the final wavelength of $\delta\lambda$

$$|T_{kl}|^2 = \frac{|T_{kl}|^2_{mea}}{|T_{11}|^2_{cal}} \qquad \frac{d\Phi_{kl}}{d\omega} = \left.\frac{d\Phi_{kl}}{d\omega}\right|_{mea} - \left.\frac{d\Phi_{11}}{d\omega}\right|_{cal} \qquad kl=11 \text{ and } 12$$
$$|T_{mn}|^2 = \frac{|T_{mn}|^2_{mea}}{|T_{22}|^2_{cal}} \qquad \frac{d\Phi_{mn}}{d\omega} = \left.\frac{d\Phi_{mn}}{d\omega}\right|_{mea} - \left.\frac{d\Phi_{22}}{d\omega}\right|_{cal} \qquad mn=21 \text{ and } 22$$

The DGD value for each wavelength is calculated using $\bar{\alpha}_1$, $\bar{\beta}_1$, $\bar{\gamma}_1$ and Θ_0 as:

$$\mathrm{DGD}(\lambda) = 2\sqrt{\bar{\alpha}_1^{\,2} + \bar{\beta}_1^{\,2} + \bar{\gamma}_1^{\,2} + 2\bar{\beta}_1\bar{\gamma}_1 \cos 2\Theta_0} \qquad (6)$$

5 Details of calculation

5.1 Examples of measurement

The calculation technique can result in a series DGD values versus wavelength. Figure 2 and figure 3 show examples of such characteristics.

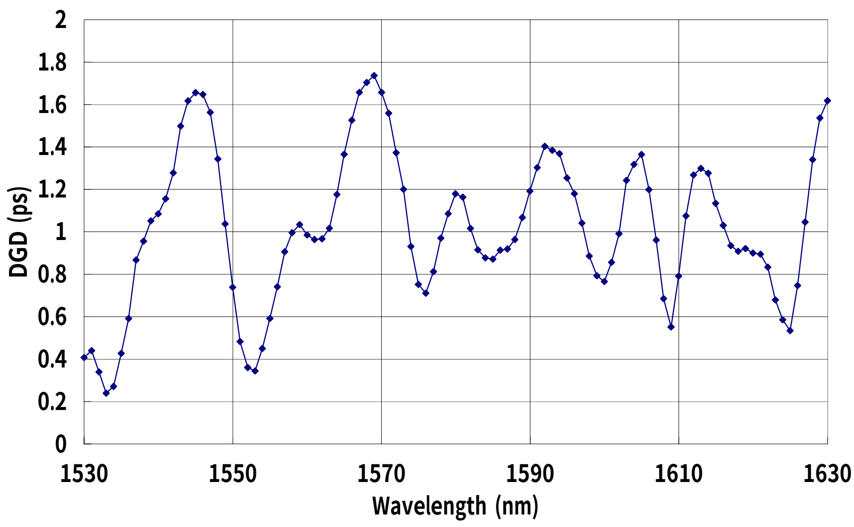

Figure 2 - DGD versus wavelength for a random mode coupling device (example)

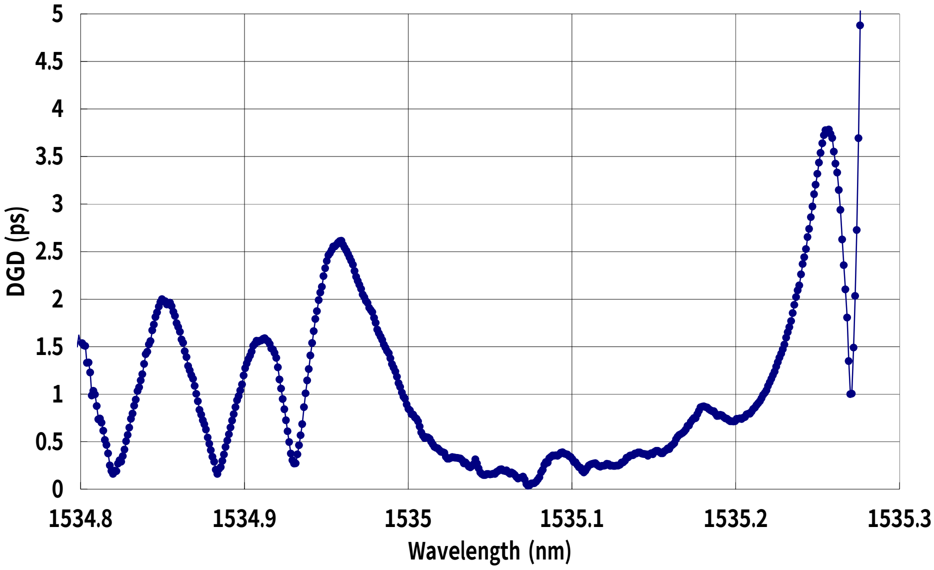

Figure 3 - DGD versus wavelength for a fibre Bragg grating filter (example)

5.2 Formulation

The definition of DGD concerning this method is described. The optical transfer function matrix can be expressed as:

$$\begin{aligned} T(\omega) &= \begin{bmatrix} |T_{11}|\cdot\exp(-j\Phi_{11}) & |T_{12}|\cdot\exp(-j\Phi_{12}) \\ |T_{21}|\cdot\exp(-j\Phi_{21}) & |T_{22}|\cdot\exp(-j\Phi_{22}) \end{bmatrix} \\ &= \begin{bmatrix} \cos\Theta\cdot\exp(-j\phi-j\psi) & -\sin\Theta\cdot\exp(-j\phi+j\psi) \\ \sin\Theta\cdot\exp(+j\phi-j\psi) & \cos\Theta\cdot\exp(+j\phi+j\psi) \end{bmatrix}\cdot\exp(-j\Phi) \end{aligned} \quad (7)$$

Where

Θ : the polarization angle

ϕ : the phase difference between T_{11} and T_{21}

ψ : the phase difference between T_{11} and T_{12}

Φ : the polarization-independent phase shift

The output polarization vector, $E^{out}(\omega)$, is expressed using $T(\omega)$ as:

$$E^{out}(\omega) = T(\omega)\cdot E^{in}(\omega) \quad (8)$$

where $E^{in}(\omega)$ is the Fourier transform of an optical input signal.

$E^{out}(\omega)$ which is described by Taylor expansion around the optical carrier frequency ω_0 is expressed as:

$$E^{out}(\omega) = E^{out}(\omega_0) + \left.\frac{dE^{out}}{d\omega}\right|_{\omega=\omega_0}\delta\omega + \frac{1}{2!}\left.\frac{d^2E^{out}}{d\omega^2}\right|_{\omega=\omega_0}\delta\omega^2 \quad (9)$$

where $\delta\omega=\omega-\omega_0$.

The first order PMD operator $D(\omega)$ that should be called a transfer function differential operator is expressed as:

$$D(\omega) = \frac{dT(\omega)}{d\omega} \cdot T(\omega)^{-1} \tag{10}$$

Therefore, the following expression is obtained by substituting (10) for (9).

$$\begin{aligned} E^{out}(\omega) &= \left\{ 1 + D\delta\omega + \frac{1}{2} D^2 \delta\omega^2 + \frac{1}{2} \frac{dD}{d\omega} \delta\omega^2 \right\} \cdot E^{out}(\omega_0) \\ &\cong \exp\left\{ D\delta\omega + \frac{1}{2} \frac{dD}{d\omega} \delta\omega^2 \right\} \cdot E^{out}(\omega_0) \end{aligned} \tag{11}$$

Where the high order term is negligible. $D(\omega)$ is the first order PMD operator and $dD(\omega)/d\omega$ is the second order PMD operator. They are not commutative with each other.

The following expression is obtained by diagonalising $D(\omega)$ with the unitary operator X.

$$\begin{aligned} X^{-1} \cdot E^{out}(\omega) &= X^{-1} \exp(D \cdot \delta\omega) X \cdot X^{-1} E^{out}(\omega_0) \\ &= \begin{bmatrix} \exp(-j\Gamma_+ \cdot \delta\omega) & 0 \\ 0 & \exp(-j\Gamma_- \cdot \delta\omega) \end{bmatrix} \cdot X^{-1} E^{out}(\omega_0) \end{aligned} \tag{12}$$

Where $-j\Gamma_{+/-}$ are the eigenvalues of $D(\omega)$ and Γ_+, Γ_- are respectively the maximum, minimum group delay.

That is, the difference between the imaginary parts of the eigenvalues of $D(\omega)$, $\Gamma_+ - \Gamma_-$, is the first order PMD called differential group delay.

Four independent parameters Θ, ϕ, ψ and Φ described in expression (7) make the following expression using Taylor expansion.

$$\begin{aligned} \Theta &= \Theta_0 + \bar{\alpha}_1 \delta\omega + \frac{1}{2} \bar{\alpha}_2 \delta\omega^2 \\ \phi &= \phi_0 + \bar{\beta}_1 \delta\omega + \frac{1}{2} \bar{\beta}_2 \delta\omega^2 \\ \psi &= \psi_0 + \bar{\gamma}_1 \delta\omega + \frac{1}{2} \bar{\gamma}_2 \delta\omega^2 \\ \Phi &= \Phi_0 + \beta_1 \delta\omega + \frac{1}{2} \beta_2 \delta\omega^2 \end{aligned} \tag{13}$$

Where

$\delta\omega = \omega - \omega_c$

Θ_0, ϕ_0, ψ_0, Φ_0 : the values of Θ, ϕ, ψ, Φ at $\omega - \omega_c$

$\bar{\alpha}_1$, $\bar{\beta}_1$, $\bar{\gamma}_1$, β_1 : the first order coefficients of Taylor expansion of Θ, ϕ, ψ, Φ

$\bar{\alpha}_2$, $\bar{\beta}_2$, $\bar{\gamma}_2$, β_2 : the second order coefficients of Taylor expansion of Θ, ϕ, ψ, Φ

The first order PMD operator $D(\omega)$ is expressed using expression (13) as:

$$D(\omega) = -j\beta_1 \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - j \begin{bmatrix} \bar{\beta}_1 + \bar{\gamma}_1 \cos 2\Theta & (-j\bar{\alpha}_1 + \bar{\gamma}_1 \sin 2\Theta) \cdot e^{-j2\phi} \\ (+j\bar{\alpha}_1 + \bar{\gamma}_1 \sin 2\Theta) \cdot e^{+j2\phi} & -\bar{\beta}_1 - \bar{\gamma}_1 \cos 2\Theta \end{bmatrix} \tag{14}$$

Therefore, the eigenvalues of $D(\omega)$ are expressed as:

$$j\Gamma_{\pm} = -j\beta_1 \pm j\sqrt{\overline{\alpha}_1^{\,2} + \overline{\beta}_1^{\,2} + \overline{\gamma}_1^{\,2} + 2\overline{\beta}_1\overline{\gamma}_1 \cos 2\Theta} \qquad (15)$$

Where β_1 is the polarization-independent group delay.

The differential group delay, $\Delta\tau$, is given by the difference between the imaginary parts of the two eigenvalues as:

$$\Delta\tau = \Gamma_+ - \Gamma_- = 2\sqrt{\overline{\alpha}_1^{\,2} + \overline{\beta}_1^{\,2} + \overline{\gamma}_1^{\,2} + 2\overline{\beta}_1\overline{\gamma}_1 \cos 2\Theta} \qquad (16)$$

5.3 PMD calculation

The PMD value within the wavelength range is given by the average value of DGD over the measured wavelength range.

6 Details to be specified

The following details, as applicable to each of the various techniques, shall be specified in the relevant specification:

6.1 Tunable Laser source

- Wavelength accuracy
- Wavelength range
- Wavelength increment

6.2 Optical intensity modulator

- Frequency bandwidth

7 References

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[3] T.Ozeki, "Mathematical analysis on definition, and statistics of polarization mode dispersion," SB-8-1, IEICE Spring Conference in Hiroshima, 2000.

[4] T.Yamashita and M.Imamura, "Simultaneous and high resolution measurement of polarization mode dispersion, group delay, chromatic dispersion and amplitude for ultra-high speed optical components", NFOEC'01, vol.3, pp.1348-1352, 2001.

Annex （informative）

The MPS and JME methods are taken up out of IEC 61300-3-32, and a comparison of specifications about applications, apparatuses, and calculations between these PMD methods and the PPS method are given in Table 1.

a) Applications

All methods can be applied to all PMD measurement of the fields from optical fibers to optical amplifiers.

b) Apparatuses

An optical intensity modulator is required for the PPS and MPS methods. In the MPS method, analysers such as polarization splitter are not necessary in optical receiver. The PPS method needs two optical receivers, the MPS needs an optical receiver, and the JME method needs four optical receivers. The PPS method need amplitude and phase comparators, the MPS method needs phase comparator, and the JME method needs amplitude comparators. A light source and a polarization controller are required for all methods.

c) Calculations

Two wavelengths are required for the PPS and JME methods for wavelength differentiation to derivation of a DGD value. The PPS method needs two linear polarized light, the JME method needs three linear polarized light, and MPS method needs all states of polarization. The PPS method needs amplitude and phase values, the MPS needs only phase values, and the JME needs only amplitude values. By using a tunable laser source, the PPS, MPS and JME methods can acquire the wavelength-dependent characteristics of DGD.

Table 1 – Comparison of the specifications between PPS, MPS, and JME methods

Items	Methods	PPS	MPS	JME
Applications	Fiber and Cables	Yes	Yes	Yes
	Un-amplified Systems/Links	Yes	Yes	Yes
	Amplified Systems/Links	Yes	Yes	Yes
	Passive Components	Yes	Yes	Yes
	Pumped Amplifiers	Yes	Yes	Yes
Apparatus	Light source	Yes	Yes	Yes
	Modulator	Yes	Yes	No
	Polarization controller	Yes	Yes	Yes
	Polarization splitter	Yes	No	Yes
	Optical receiver(s)	Yes (2)	Yes (1)	Yes (4)
	Amplitude & Phase comparator	Yes (A & P)	Yes (P)	Yes (A)
Calculations	$\Delta\lambda$	Yes	No	Yes
	SOPs	2 states	All states	3 states
	Amplitude	Yes	No	Yes
	Phase	Yes	Yes	No
	DGD(λ)	Yes	Yes	Yes

Table 2 gives a comparison of application scope of various PMD measurement methods for passive optical components. The JME and PSA methods have sufficient measurement accuracy to all passive optical components. The PPS method has sufficient measurement accuracy to all passive optical components except very low PMD components such as 0.1ps or less. The PPS method has the advantage that not only PMD but also all the transmission characteristics for passive optical components such as loss, GD, CD, and second order PMD can be measured.

Table 2 – Comparison of PMD measurement methods for passive optical components

Methods			PPS	INT	MPS	JME/PSA	FA
Measurement Items	PMD	PMD	YES	YES	YES	YES	YES
			(PMD value is the average of the DGD value.)	(Definition of PMD differs according to mode coupling.)	(PMD value is the average of the DGD value.)	(PMD value is the average of the DGD value.)	(A mode coupling constant K is used according to DUT.)
		DGD(λ)	YES	NO	YES	YES	NO
		Isolators, Circulators (0.1～0.8ps)	GOOD	GOOD	POSSIBLE	GOOD	POSSIBLE
		DWDM filters (0.3～0.5ps)	GOOD	NG	GOOD	GOOD	NG
		DCM (0.6～3ps)	GOOD	GOOD	GOOD	GOOD	NG
				(except DWDM filter type)			
		Others (<0.1ps)	POSSIBLE	GOOD	POSSIBLE	GOOD	NG
	Loss		YES	NO	YES	YES	NO
	Group delay		YES	NO	YES	NO	NO
	Chromatic dispersion		YES	NO	YES	NO	NO
	Second order PMD		YES	NO	NO	YES	NO
PMD Measurement accuracy			0.02ps@2.5GHz	0.003 to 0.05ps	0.09ps@2GHz	0.01ps	0.1ps
PMD Measurement Speed			FAST	FAST	SLOW	SLOW	FAST
Cost of apparatus			HIGH	LOW	HIGH	LOW	LOW
Advantage			It is possible to measure simultaneously not only PMD but also GD, CD and 2nd order PMD.	It is possible to measure very low PMD.	It is possible to measure simultaneously not only PMD but also GD, CD.	It is possible to measure simultaneously not only PMD but also 2nd order PMD. It is applicable for all passive components.	Simple apparatus.

Key:

GOOD Applicable
POSSIBLE Applicability is limited in scope, range or performance, or applicability not yet confirmed.
NG Inapplicable

Key to PMD measurement methods:

PPS = Polarization phase shift method
INT = Interferometric method
MPS = Modulation phase shift method
JME = Jones matrix eigenanalysis method
PSA = Poincare sphere analysis method
FA = Fix analyzer method
DCM = Dispersion compensating module

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発行者：財団法人　光産業技術振興協会
住所：〒112-0014 東京都文京区関口 1-20-10
住友江戸川橋駅前ビル 7F
電話：03-5225-6431　FAX：03-5225-6435
e-mail:opt-st@oitda.or.jp　（標準化室）