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Chromatic dispersion measurement using polarization phase shift (PPS) 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波長分散測定方法）

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Chromatic dispersion measurement using polarization phase shift（PPS）method for passive optical components

（偏波位相シフト法による光受動部品の波長分散測定方法）

1 Scope

The purpose of this measurement procedure is to present a method to measure the chromatic dispersion (CD) of passive optical components. This procedure will cover measurements of both wide band and narrow band components, and dense wavelength division multiplexing (DWDM) components such as DWDM filters. This procedure can be applied to laboratory, factory and field measurements of CD 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 shall be very low CD value.

2 Normative references

IEC 61280-4-4: Polarization mode dispersion (PMD) 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

Figure 1 shows a block diagram of the polarization phase shift method (PPS).

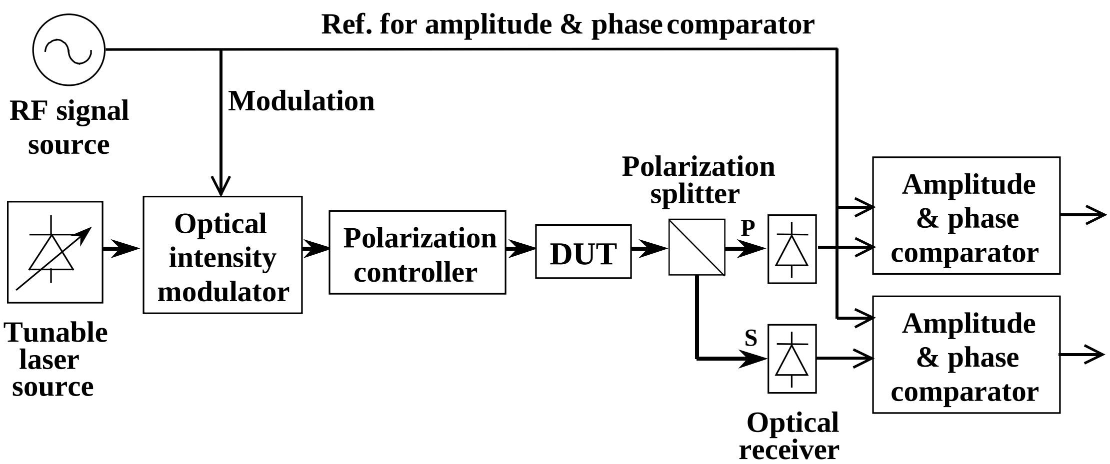

Figure 1 – Block diagram for PPS

3.1 Tunable laser source

A tunable laser source is used as the light source. The wavelength tuning range of the laser shall be sufficient to cover the wavelength range for to be measured. And, to get the excellent SNR and wavelength resolution of the measurement result, it is necessary that its optical output power is more than 0dBm, the spectral line width is less than 50MHz and it can sweep the wavelength continuously. Generally, the completely self-contained temperature controlled and current controlled wavelength stabilized external cavity laser unit is employed. The output of the tunable laser source 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 modulated pattern for the optical intensity modulator. Some of the modulated pattern 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 modulated pattern whose frequency range is typically from 50MHz to 3GHz. In the selection of the modulation frequency undesirable influences of modulation sidebands and the CD measurement resolution shall 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:

$$\Delta\lambda = 2 \cdot \frac{\lambda^2 \cdot f}{c} \qquad (1)$$

Where
- λ : wavelength (nm)
- f : modulation frequency (GHz)
- c : velocity of light in vacuum (m/s)

In addition, the CD measurement resolution, ΔCD(ps/nm), is also restricted by the modulation frequency, f, and is typically given as:

$$\Delta CD = \frac{\Delta\tau}{\Delta\lambda} = \frac{\Delta\phi \cdot 10^3}{360 \cdot f} \cdot \frac{1}{\Delta\lambda} \qquad (2)$$

Where
- $\Delta\phi$: phase resolution of the phase comparator (degree)
- f : modulation frequency (GHz)
- $\Delta\tau$: group delay (GD) resolution（ps）
- $\Delta\lambda$: wavelength resolution（nm）

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

3.2.2 Optical intensity modulator

The optical intensity modulator modulates the intensity of light from the tunable laser source synchronize to the modulated pattern from RF signal source. The insertion loss of the optical intensity modulator shall be used less than 5dB. The on-off extinction ratio and the polarization extinction ratio of the optical intensity modulator shall be more than 20dB respectively. The optical performances such as insertion loss, on-off extinction ratio and polarization extinction ratio shall be satisfied the required value over the wavelength range to be measured. In order to achieve these performances, generally $LiNbO_3$ (LN) modulator is used. A polarization maintaining fiber is used as an input fiber in order to connect with a tunable laser source. A driving 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 approximately 20%.

3.3 Polarization controller

The polarization controller is used to launch light of specific states of polarization (SOP) 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 angle adjustable resolution is shall be less than +/-0.1 degree and the polarization extinction ratio shall be more than 30dB over the wavelength range to be measured.

3.4 Polarization splitter

The polarization splitter is placed after the DUT. The output light is separated into two independent polarized waves, P- and S-polarised lights. And each light leads to the optical receivers. The polarization splitter consists of a non-isotropic crystal such as a calcite prism possessing a high polarization extinction ratio, such as more than 30dB. The insertion loss shall be less than 1dB. The optical performances such as polarization extinction ratio and insertion loss of the polarization splitter shall 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 approximately $10\mathrm{pA/(Hz)}^{1/2}$, is generally used. The PIN photodiode must have response 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 shall be used 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 polarized wave with the reference signal from the RF signal source. The GD, τ (ps), is calculated from the phase using the following equation:

$$\tau = \frac{\phi \cdot 10^3}{360 \cdot f} \qquad (3)$$

Where
ϕ: phase (degree)
f: modulation frequency (GHz)

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

4 Procedure

4.1 Modulation frequency

The modulation frequency shall be chosen based on the wavelength resolution $\Delta\lambda$ and GD $\Delta\tau$. For more information, refer to Section 3.2.1.

4.2 Wavelength increment

Two wavelengths are required to obtain a CD value because the wavelength differentiation in this wavelength increment, $\delta\lambda$, is used when calculating a CD. The phase difference that can be measured with the phase comparator is within +/-180 degrees. Therefore, the maximum GD, $\Delta\tau_{max}$, that can be measured between the adjoined wavelengths are shown by the following expression.

$$\Delta\tau_{\max} \le \left| \pm \frac{180}{360} \cdot \frac{10^3}{f} \right| = \frac{10^3}{2f} \tag{4}$$

This wavelength increment, $\delta\lambda$, will be called wavelength step size. To obtain the wavelength resolution of CD that shall be achieved, the wavelength step size is decided as follows.

$$\delta\lambda \le \left| \pm \frac{\Delta\tau_{\max}}{CD_{\max}} \right| \tag{5}$$

Where

$\delta\lambda$: wavelength step size (nm)

$\Delta\tau_{max}$: maximum GD of DUT (ps)

f : modulation frequency（GHz）

CD_{max}: maximum CD（ps/nm）

4.3 Scanning wavelength and measuring CD

The tunable laser source is used to perform a wavelength sweep along the desired wavelength range, and the GD value is calculated at each wavelength. In addition, the CD value of the DUT can be calculated from the wavelength differentiation of the GD value in each measurement wavelength based on the GD value that has been obtained.

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

4.4 Calibration

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

4.5 CD calculation

The P- and S-polarized light GDs are calculated using measured values in Section 4.3 and 4.4.

P-polarized light GD: $\frac{d\Phi_{kl}}{d\omega} = \frac{d\Phi_{kl}}{d\omega}_{mea} - \frac{d\Phi_{11}}{d\omega}_{cal}$ kl=11 and 12

Average GD in P-polarized light: $\frac{d\Phi_{ave1}}{d\omega} = \left(\frac{d\Phi_{11}}{d\omega} + \frac{d\Phi_{12}}{d\omega}\right) \Big/ 2$ (6)

S-polarized light GD: $\frac{d\Phi_{mn}}{d\omega} = \frac{d\Phi_{mn}}{d\omega}_{mea} - \frac{d\Phi_{22}}{d\omega}_{cal}$ mn=21 and 22

Average GD in S-polarized light: $\frac{d\Phi_{ave2}}{d\omega} = \left(\frac{d\Phi_{21}}{d\omega} + \frac{d\Phi_{22}}{d\omega}\right) \Big/ 2$ (7)

The GD and CD values on each wavelength are calculated by the next expressions.

GD that doesn't depend on polarization: $GD(\lambda) = \left(\frac{d\Phi_{ave1}}{d\omega} + \frac{d\Phi_{ave2}}{d\omega}\right) \Big/ 2$ (8)

CD that doesn't depend on polarization: $CD(\lambda) = \frac{(GD(\lambda + \Delta\lambda) - GD(\lambda - \Delta\lambda))}{2 \cdot \Delta\lambda}$ (9)

The error of measurement caused by PMD can be excluded from the measurement result by obtaining GD and CD that doesn't depend on the polarization.

5 Examples of measurement

This procedure can measure the wavelength characteristics of CD. Figure 2 and Figure 3 show the examples of GD and CD measurement for a device without the mode coupling.

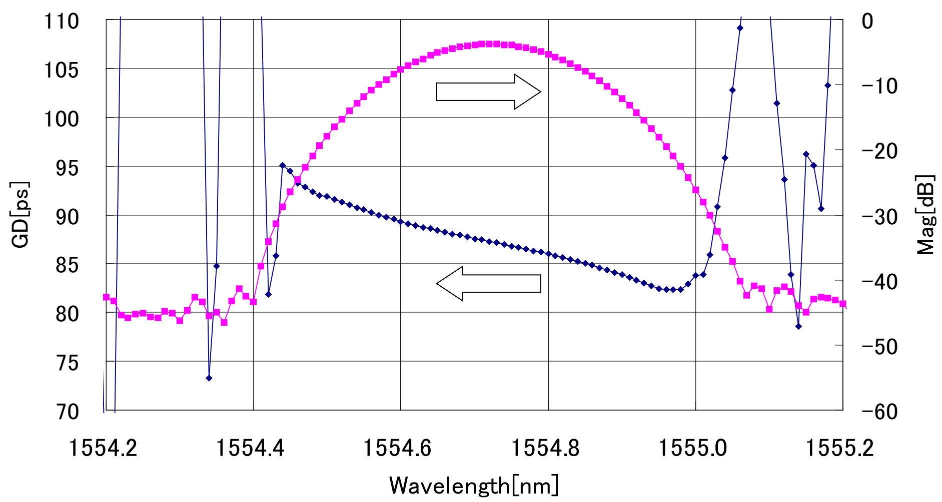

Figure 2 Measured GD for a device without mode coupling

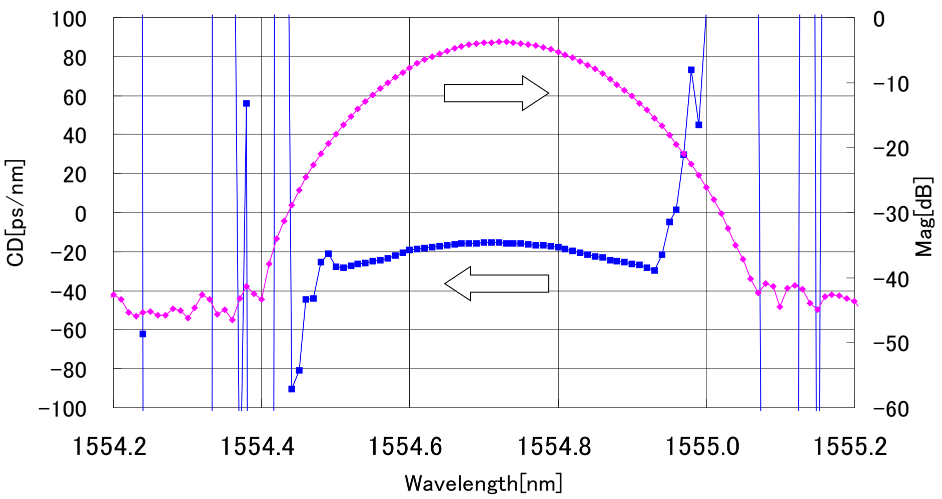

Figure 3 Measured CD for a device without mode coupling

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

[1] K. Sano, T. Kudou and T. Ozeki, “Simultaneous measurement of group delay time dispersion and polarization mode dispersion,” ECOC’96 , TuP-09, pp.253-256, 1996.

[2] K. Sano, T. Kudou and T. Ozeki, “A new measurement method of polarization mode dispersion,” OECC’96, 17C1-4, 1996.

[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

The polarization phase shift method (PPS) can measure the CD, GD, insertion loss, PMD and 2nd-order PMD simultaneously with good enough accuracy. The PPS has already been described in the document "Polarization mode dispersion measurement for installed links (IEC 61280-4-4)" under discussing with IEC 86C/WG1.

Comparison between the PPS and other metrologies is described below.

a) Applications

Both PPS and the MPS can be applied to CD measurement for all optical devices including optical fibres and optical amplifiers.

b) Apparatuses

An optical intensity modulator is required for both the PPS and the MPS. The MPS does not need a polarization splitter before an optical receiver. The PPS needs two optical receivers. The PPS needs amplitude and phase comparators. The MPS needs a phase comparator. A light source and a polarization controller are required for both methods.

Table 1 shows a comparison of application scope of various CD/PMD measurement methods for passive optical components.

Table 1-Comparison of CD/PMD measurement methods for passive optical components

parameter	DUT*1	measurement methods						
		PPS	MPS	Swept wavelength interferometry (SWI)	Interferometry (INT)	Differencial phase shift	Pulse delay method	OTDR
CD[ps/nm]	long fiber*2	good	good	no	no	possible*4	possible*5	possible*5
	DWDM filter	good	good	good	no	possible*4	no*6	no*6
	other passive optical components	good	good	good	good	possible*4	no*6	no*6
GD[ps]	long fiber*2	good	good	no	no	possible*4	good	good
	DWDM filter	good	good	good	no	possible*4	no*6	no*6
	other passive optical components	good	good	good	good	possible*4	no*6	no*6
GDR[ps]*3	long fiber*2	good	good	no	no	no	no	no
	DWDM filter	good	good	good	no	no	no	no
	other passive optical components	good	good	good	no	no	no	no
PMD[ps]	long fiber*2	good	good	no	no	no	no	no
	DWDM filter	good	good	good	no	no	no	no
	other passive optical components	good	good	good	possible*7	no	no	no
2nd order PMD[ps2]	long fiber*2	possible	no	no	no	no	no	no
	DWDM filter	possible	no	possible	no	no	no	no
	other passive optical components	possible	no	possible	no	no	no	no
Insertion loss[dB]	—	good	good	good	no	good	no	good
PDL[dB]	—	possible	possible	possible*8	no	no	no	no
Features in measurement	measurement ends	both ends	both ends	both ends	both ends	both ends	both ends	one end
	phase or time domain measurement	phase domain	phase domain	time domain	time domain	phase domain	time domain	time domain
	PMD measurement speed	fast	slow	fast	fast	no	no	no
	configuration	complex	complex	simple	simple	complex	simple	simple

*1: DUT was chosen because of the delay time and wavelength range.
*2: Length of an optical fiber (or DCF) is more than several ten meters.
*3: "good""possible""no" was presumed from a technical view point. It is necessary to confirm their performance, accuracy and
*4: The principle of the differential phase shift method looks like the modulation phase shift method. Moreover, it can measure DCF and other optical passive components. However, because the catalog specification value was different, it was assumed "possible"
*5: Because only repeatability was provided by the catalog specification, the pulse delay method and the OTDR method were
*6: It is unsuitable to the measurement of passive optical components with small dipsersion value because of the measurement time
*7: Wavelength dependancy of PMD can not be measured. PMD definitions are different by the mode coupling conditions.
*8: Long fiber can not be measured.

Figure 4 and figure 5 show GD and CD measurement examples with PPS and MPS for a device without mode coupling. The measurement result by the PPS is in good accordance with the measurement result by the MPS. And, it can measure the GD and the CD in high accuracy as well as the MPS.

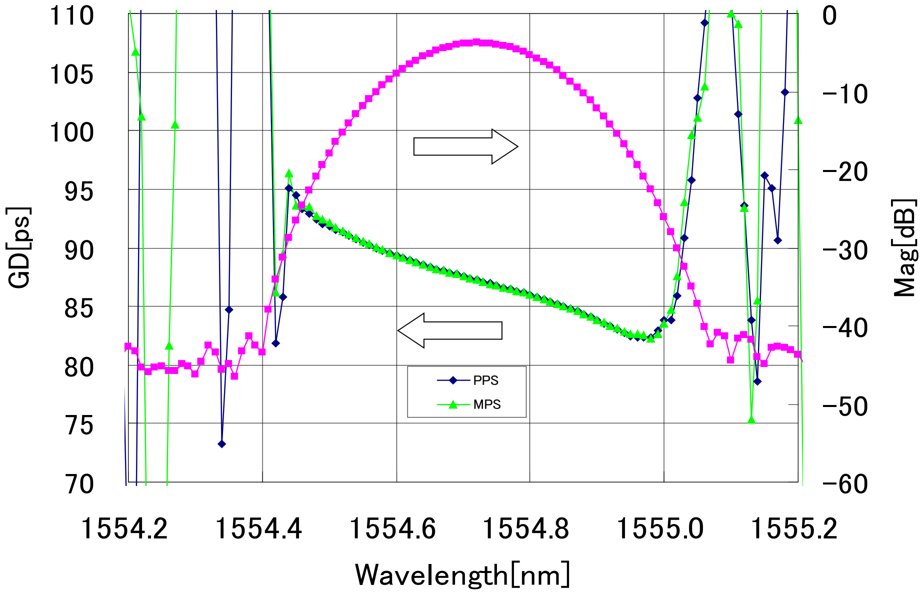

Figure 4 Measured GD for a device without mode coupling

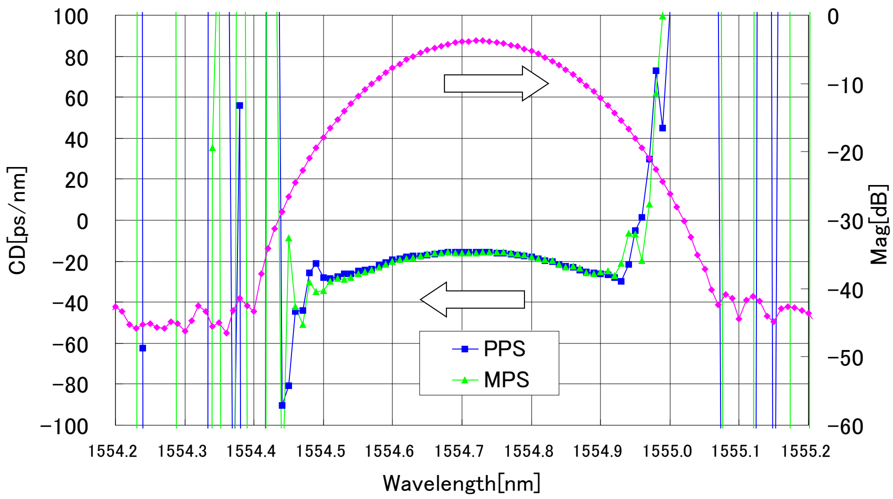

Figure 5 Measured CD for a device without mode coupling

Figure 6 shows a GD measurement example for a device with random mode coupling. Even if for a device with PMD, PPS can measure GD characteristics accurately.

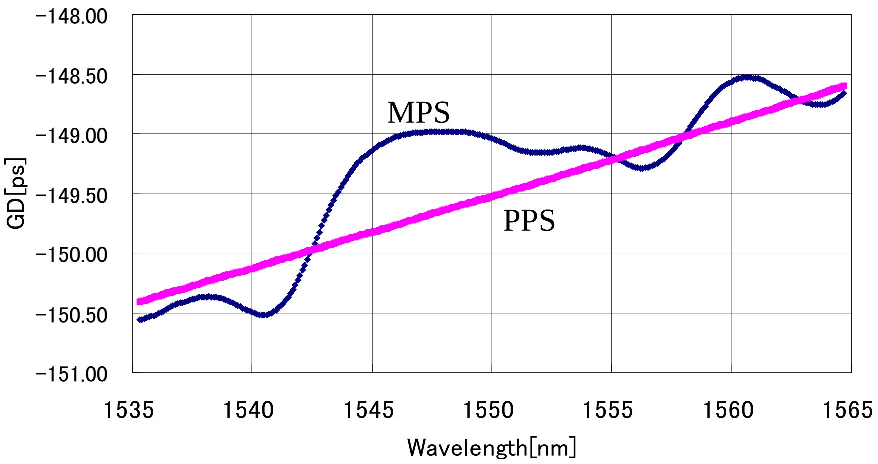

Figure 6 Measured GD for a device with random mode coupling

Figure 7 shows a CD measurement example for a device with random mode coupling. Even if for a device with PMD, PPS can measure CD characteristics accurately.

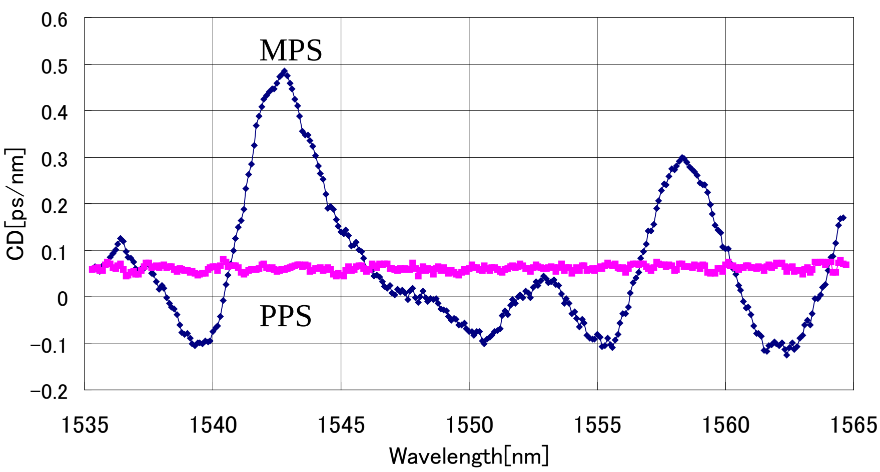

Figure 7 Measured GD for a device with random mode coupling

解　説

1.　制定の目的，経緯

偏波位相シフト(PPS： Polarization Phase Shift)法による波長分散（CD）測定は，供試品の CD 特性と偏波モード分散（PMD）特性を明確に分離して測定することができる優位性がある。

2004 年 9 月に開催された IEC ワルシャワ会合 TC86/WG4 にて新しい PMD 測定法として本測定法を紹介した際，本測定法も光受動部品の波長分散測定法(IEC61300-3-38)に追加することで検討を進めることとなった。

これを受けて光受動部品標準化委員会では，2005 年度より PPS 法による CD 測定法の規格案(和文)の検討を進めてきた。2006 年度は供試品を測定･評価する観点から，代表的な CD 測定法の特徴を比較表として整理し，英文化作業を進めた。

測定法の比較表は，光ファイバや DWDM フィルタなど供試品の種類や，CD 測定に加え PMD や挿入損失など他の測定パラメータや得られる測定精度など，利用者がそれぞれの測定法の特徴を理解し，測定の目的に応じて適切な測定法を選択することができるよう整理した。

2.　測定法の概要

本測定法は，光受動部品の新しい波長分散（CD）測定法である。本測定法のブロック図を図に示す。波長可変光源からの出力光は，光強度変調器に入力され正弦波強度変調光となる。この変調光は，偏波コントローラを通過したのち被測定デバイス（DUT）に入力される。DUT を通過した光は，偏光スプリッタによって二つの偏波成分に分離され，それぞれの光検出器によって電気信号に変換されたのち振幅/位相比較器に入力される。振幅/位相比較器では，RF 信号源からの参照信号との間で振幅/位相比較されることにより，振幅と位相が測定される。これを偏波コントローラから出力される二つの直交した直線偏波に対してそれぞれ行うことで，DUT の光伝達関数行列の情報を含んだデータ，すなわち電力振幅 $|T_{ij}|^2$ と群遅延 $d\Phi_{ij}/d\omega$ が測定される。これらの測定データを用いることで，CD を求めることができる。

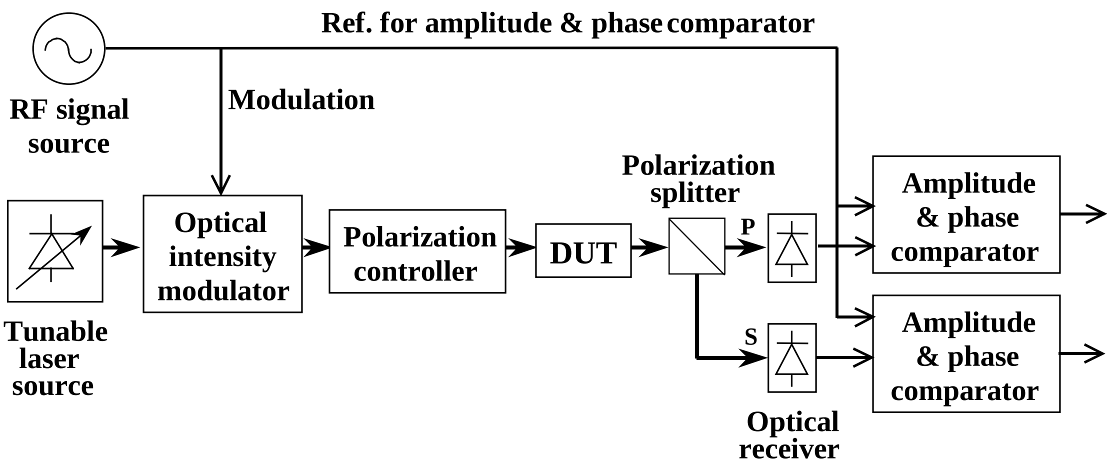

図　偏波位相シフト法のブロックダイアグラム

3. 審議委員会

この規格の審議は，主に光受動部品標準化委員会が行った。以下にその委員を示す。

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