BS EN 61300-3-38:2012

BSI Standards Publication

Fibre optic interconnecting devices and passive components — Basic test and measurement procedures

Part 3-38: Examinations and measurements — Group delay, chromatic dispersion and phase ripple

NO COPYING WITHOUT BSI PERMISSION EXCEPT AS PERMITTED BY COPYRIGHT LAW

raising standards worldwide™

National foreword

This British Standard is the UK implementation of EN 61300-3-38:2012. It is identical to IEC 61300-3-38:2012.

The UK participation in its preparation was entrusted by Technical Committee GEL/86, Fibre optics, to Subcommittee GEL/86/2, Fibre optic interconnecting devices and passive components.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

© The British Standards Institution 2012

Published by BSI Standards Limited 2012

ISBN 978 0 580 59513 4

ICS 33.180.10

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 30 September 2012.

Amendments issued since publication

Amd. No.	Date	Text affected

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN 61300-3-38

August 2012

ICS 33.180.10

English version

Fibre optic interconnecting devices and passive components - Basic test and measurement procedures - Part 3-38:Examinations and measurements - Group delay, chromatic dispersion and phase ripple
(IEC 61300-3-38:2012)

Dispositifs d’interconnexion et composants passifs à fibres optiques - Procédures fondamentales d'essais et de mesures - Partie 3-38: Examens et mesures - Retard de groupe, dispersion chromatique et fluctuation de phase
(CEI 61300-3-38:2012)

Lichtwellenleiter - Verbindungselemente und passive Bauteile - Grundlegende Prüf- und Messverfahren - Teil 3-38: Untersuchungen und Messungen - Gruppenlaufzeitverzögerung, chromatische Dispersion und Phasenwelligkeit
(IEC 61300-3-38:2012)

This European Standard was approved by CENELEC on 2012-07-03. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN-CENELEC Management Centre or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the CEN-CENELEC Management Centre has the same status as the official versions.

CENELEC members are the national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, Former Yugoslav Republic of Macedonia, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

CENELEC

European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

Management Centre: Avenue Marnix 17, B - 1000 Brussels

© 2012 CENELEC - All rights of exploitation in any form and by any means reserved worldwide for CENELEC members.

Ref. No. EN 61300-3-38:2012 E

Foreword

The text of document 86B/3394/FDIS, future edition 1 of IEC 61300-3-38, prepared by SC 86B "Fibre optic interconnecting devices and passive components" of IEC TC 86 "Fibre optics" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 61300-3-38:2012.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2013-04-03
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2015-07-03

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 61300-3-38:2012 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60793-1-42	NOTE	Harmonised as EN 60793-1-42.
IEC 61300-1	NOTE	Harmonised as EN 61300-1.
IEC 61300-3-1	NOTE	Harmonised as EN 61300-3-1.
IEC 61300-3-32	NOTE	Harmonised as EN 61300-3-32.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60050-731	-	International Electrotechnical Vocabulary (IEV) - Chapter 731: Optical fibre communication	-	-
IEC 61300-3-29	-	Fibre optic interconnecting devices and passive components - Basic test and measurement procedures - Part 3-29: Examinations and measurements - Measurement techniques for characterising the amplitude of the spectral transfer function of DWDM components	EN 61300-3-29	-

CONTENTS

FIBRE OPTIC INTERCONNECTING DEVICES AND PASSIVE COMPONENTS – BASIC TEST AND MEASUREMENT PROCEDURES –

Part 3-38: Examinations and measurements – Group delay, chromatic dispersion and phase ripple

1 Scope

This part of IEC 61300 describes the measurement methods necessary to characterise the group delay properties of passive devices and dynamic modules. From these measurements further parameters like group delay ripple, linear phase deviation, chromatic dispersion, dispersion slope, and phase ripple can be derived. In addition, when these measurements are made with resolved polarization, the differential group delay can also be determined as an alternative to separate measurement with the dedicated methods of IEC 61300-3-32.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-731, *International Electrotechnical Vocabulary – Chapter 731: Optical fibre communication*

IEC 61300-3-29, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 3-29: Examinations and measurements – Measurement techniques for characterizing the amplitude of the spectral transfer function of DWDM components*

3 Terms and abbreviations

For the purposes of this document, the terms and definitions given in IEC 60050-731 and IEC 61300-3-29 apply, together with the following.

BW	Bandwidth: the spectral width of a signal or filter.
CD	Chromatic dispersion (in ps/nm): change of group delay over wavelength: CD=d(GD)/dλ
D	Detector
DGD	Differential group delay (in ps): difference in propagation time between two orthogonal polarization modes
DUT	Device under test
DWDM	Dense wavelength division multiplexing
δ	Step size of the VWS during a wavelength swept measurement
f_{RF}	Modulation frequency
GD	Group delay (in ps): time required for a signal to propagate through a device
GDR	Group delay ripple (in ps): the amplitude of ripple of GD
LN	$LiNbO_3$

LPV	Linear phase variation (in deg)
λ_c	Centre channel or nominal operating wavelength for a component
MPS	Modulation phase shift
PBS	Polarising beam splitter
PMD	Polarization mode dispersion (in ps): average value of DGD over wavelength
PPS	Polarization phase shift
PSP	Principle state of polarization
Φ	Phase delay
RBD	Reference branching device
SOP	State of polarization
SSE	Source spontaneous emission
SWI	Swept wavelength interferometry
$\Delta\theta$	Phase ripple
TDC	Tunable dispersion compensator
TJ	Temporary joint
TLS	Tunable laser source
VWS	Variable wavelength source

4 General description

This document covers transmission measurements of the group delay properties of passive devices and dynamic modules. In order to interpret the group delay properties, it is essential to also have the amplitude spectral measurement available. For this reason, loss measurements are also covered to the extent that they are required to make proper dispersion measurements.

The methods described in this procedure are intended to be applicable in any wavelength band (C, L, O, etc.) although examples may be shown only in the C band for illustrative purposes.

This document is separated into two sections, one concentrating on measurement methods, and one concentrating on analysis of the measurement data. The measurement methods covered in this document are the modulation phase shift method, the swept-wavelength interferometry method and the polarization phase shift method. The modulation phase shift method is considered the reference method. The methods are selected particularly because of their ability to provide spectrally resolved results, which are often necessary for passive components and especially for wavelength-selective devices.

The appropriate measurement parameter to evaluate the group delay ripple, and the method of estimating the phase ripple from the measurement result of GDR are shown in 7.4. The phase ripple is important as a measure of the influence that GD of an optical device has on the transmission quality since many tunable dispersion compensators use the interference effect where ripple is a significant effect.

5 Apparatus

5.1 Modulation phase shift method

5.1.1 General

The measurement set-up for the characterisation of the group delay (GD) properties of optical components is shown in Figure 1. A detailed explanation of the various components of this system and their functions is contained in 5.1.2 to 5.1.13.

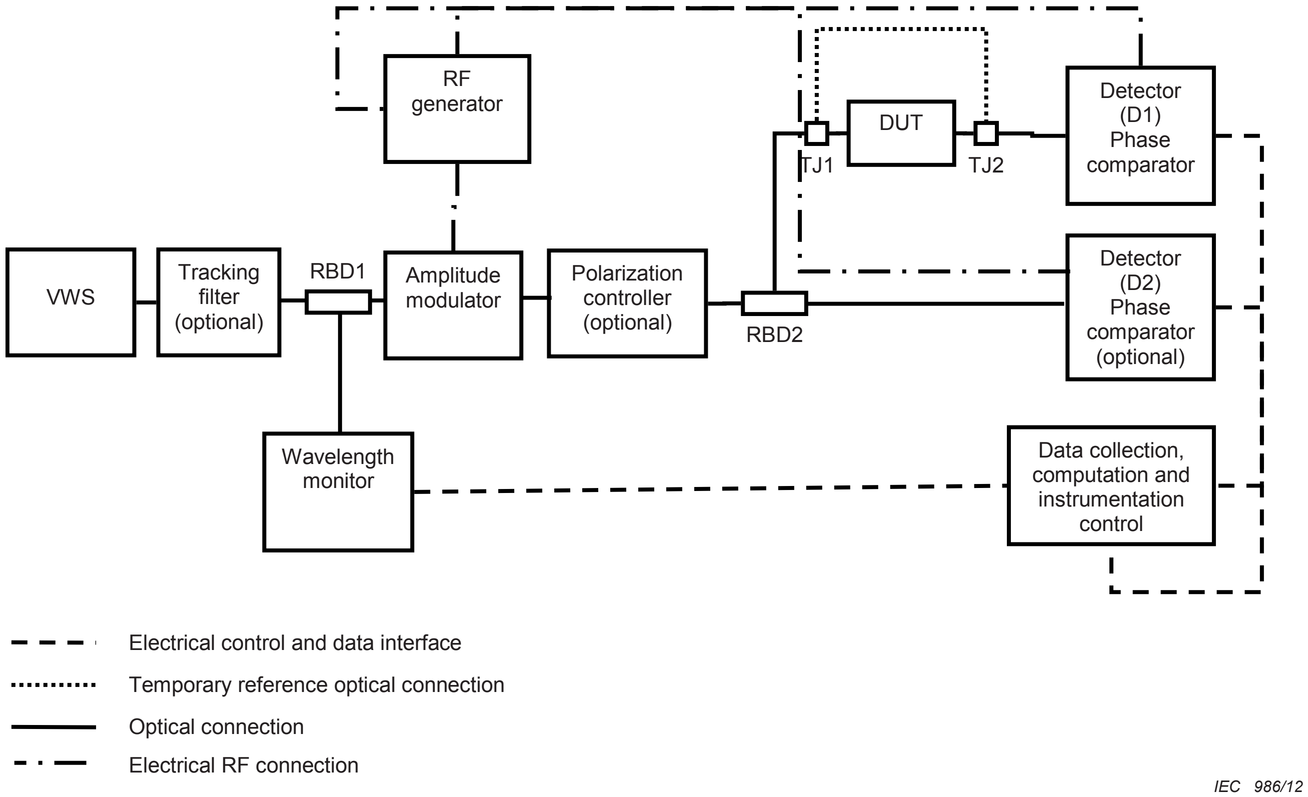

Figure 1 – MPS measurement method apparatus

5.1.2 Variable wavelength source VWS

The variable wavelength source (VWS) is a polarized light source that can select a specific output wavelength and can be tuned across a specified wavelength range. The power stability at any of the operating wavelengths shall be sufficient so as not to cause significant errors in the phase comparators. The relative accuracy and repeatability of wavelength, as determined by the VWS and wavelength monitor together, shall be accurate to 3 pm for each point in the measuring range and the absolute wavelength accuracy should satisfy the wavelength specifications of the device under test. The linewidth of the source shall be less than 100 MHz. The tuning range of the VWS shall cover the entire spectral region of the device and the source shall also be free of mode hopping over the tuning range. The output power of the VWS shall be sufficient to provide enough signal to ensure good comparison of the phase.

The minimum increment of the wavelength of the VWS should be adjusted to one tenth of expected GDR period of the DUT.

5.1.3 Tracking filter (optional)

The tracking filter may be used for any DUT measurements if the dynamic range of the VWS and the detector does not allow for measuring dynamic range of at least 40 dB due to the shape of the DUT and the broadband source spontaneous emission (SSE) of the VWS. The filter shall track the VWS so as to provide the maximum SSE suppression and the maximum transmitted power as the VWS is scanned across the measurement region. The spectral shape of the filter shall provide enough out of band attenuation to allow for 40 to 50 dB dynamic range at the transmission detector.

5.1.4 Reference branching device RBD1, RBD2

The configuration of the RBD is 1 × 2 or 2 × 2. If its configuration is 2 × 2, one port of the RBD shall be terminated to have a return loss better than 50 dB. The splitting ratio of the RBD shall be stable with wavelength. It shall also be insensitive to polarization. The polarization sensitivity of transmission attenuation shall be less than one tenth of the device wavelength dependency of attenuation or less than 0,1 dB. The directivity shall be at least 10 dB higher than the maximum return loss. The split ratio shall be sufficient to provide the dynamic range for the measurement of the transfer function and the power necessary for the wavelength monitor to operate correctly.

5.1.5 Wavelength monitor (optional)

In this test procedure, the wavelength accuracy of the source needs to be closely monitored. If the tuning accuracy of the VWS is not sufficient for the measurement, a wavelength monitor is required. For this measurement method, it is necessary to measure the spectral peak of any input signal within the device BW to an accuracy of 3 pm. Acceptable wavelength monitors include an optical wavelength monitor or a gas absorption cell (such as an acetylene cell). If a gas absorption cell is used, the wavelength accuracy of the VWS must be sufficient to resolve the absorption lines. The VWS must be sufficiently linear between the absorption lines.

Included under this specification, is the wavelength repeatability of the VWS + monitor. It should be understood by the operator that if the test apparatus has 0,1 ps of ripple with a 30 pm period, then a random 3 pm wavelength variation from reference scan to device scan can result in as much as 0,03 ps of GD noise.

5.1.6 Device under test DUT

For the purposes of this document, the test ports shall be a single “input-output” path. The method described can be extrapolated to obtain a single measurement system capable of handling an m x n device. The device shall be terminated on either pigtails or with connectors. Because this measurement set up is very sensitive to reflections, and is useful for detecting reflections in the DUT it is important that reflections are not introduced by the measurement system.

In many cases, the characteristics of DWDM components are temperature dependent. This measurement procedure assumes that any such device is held at a constant temperature throughout the procedure. The absolute accuracy of the measurement may be limited by the accuracy of any heating or cooling device used to maintain a constant temperature. For example, if a device is known to have a temperature dependence of 0,01 nm / C, and the temperature during the procedure is held to a set temperature ± 1 °C; then any spectral results obtained are known to have an total uncertainty of 0,02 nm due to temperature.

5.1.7 Detectors D1, D2

The detectors consist of an optical detector, the associated electronics, and a means of connecting to an optical fibre. The use of a detector (D2) is considered optional, but provides correction for any instability in the GD of the instrument setup between the modulator and the DUT between Step 3 and Step 4 of 6.1.3. The optical connection may be a receptacle for an optical connector, a fibre pigtail, or a bare fibre adapter. The back-reflection from detectors D1 and D2 shall be minimised. The preferred option would be to use an APC connector. It should be noted that the use of an APC connector would contribute approximately 0,03 dB of PDL to the measurement if terminated in air.

The dynamic range and sensitivity of the detectors shall be sufficient for the required measurement range, given the power level provided by the modulated source. The linearity of the detectors shall be sufficient to provide accurate representation of the modulated signal. The detector shall transfer the optical modulation phase to the RF output phase with good stability and little dependence on the optical signal level.

Where during the sequence of measurements a detector shall be disconnected and reconnected the coupling efficiency for the two measurements shall be maintained to at least the accuracy of the mated connector.

5.1.8 RF generator

The RF Generator delivers an electrical signal that is used for driving the intensity modulator. In addition, the signal is delivered to the phase comparator in detectors D1 and D2 as a reference signal. The RF Generator produces a waveform with a single dominant Fourier component, for example, a sinusoidal wave modulation. Typically, a sinusoidal signal with a frequency in the range of 100 MHz up to 3 GHz is used. The RF generator shall have sufficient frequency accuracy and stability for the required measurement accuracy, considering that the frequency provides the time base for the GD measurement.

5.1.9 Amplitude modulator

The amplitude modulator uses the modulated signal from the RF generator to induce the equivalent amplitude modulation on a continuous wave optical signal. The modulator converts the modulated signal from the RF generator to a modulated optical signal. The modulator shall have sufficient linearity to produce a good sinusoidal modulation. The modulation amplitude should be matched to the dynamic range of the detector system.

5.1.10 Phase comparator

The phase comparator is built into the detectors D1 and D2, which compare the phase of the modulated optical signal and the RF reference signal. Typically, a network analyser, or lock-in amplifier is used as a phase comparator. A method known as phase sensitive detection is used to single out the component of the signal at a specific reference frequency and phase. Noise signals at frequencies other than the reference frequency are rejected and do not affect the phase measurement. The RF signal level shall not affect the phase measurement.

5.1.11 Temporary joints TJ1, TJ2

Temporary joints are specified to connect the test input signal to the device under test to the device output to the transmission detector (D1).

Examples of temporary joints are typically connectors or splices. However other methods such as vacuum chucks, or micromanipulators may be applied. Due to the high sensitivity to back reflections, it is necessary to ensure that all of these joints have back-reflection <-50 dB.

5.1.12 Polarization controller (optional)

The modulated laser signal is optionally sent to a polarization controller, wherein the polarization can be adjusted to the 4-Mueller-states located on the surface of the Poincaré sphere, three of them on the equator of the Poincaré sphere and separated by 90 degree consisting of the 0º, 45º and 90º linear polarization states, and the fourth state on the pole of the Poincaré sphere for circular polarization. If the DUT exhibits polarization mode dispersion, averaging results from orthogonal polarization states allows the GD average over all input polarization states to be determined. From a set of GD measurements at all the 4-Mueller-states, the differential group delay (DGD) can be calculated. The polarization controller shall be able to provide satisfactory polarization stability over the wavelength range of the measurement.

5.1.13 Reference jumper

The reference jumper is a single-mode fibre. The optical connection may be an optical connector, a fibre pigtail, or a bare fibre. The reference jumper must have the same optical connection as the DUT.

5.2 Swept wavelength interferometry method

5.2.1 General

The measurement set-up for this method is shown in Figure 2. A detailed explanation of the various components of this system and their functions is contained in 5.2.2 to 5.2.7. The setup shown illustrates a transmission measurement of a DUT with two optical ports.

The measurement of GD is usually of interest to determine its dependence on wavelength and polarization. However, the GD of optical fibre and other components of optical fibre networks is also sensitively dependent on outside parameters such as temperature, pressure, mechanical stress, and noise. Therefore a setup for measuring GD should provide for stability against fibre movement and external changes during the measurement. Since the SWI method relies on tracing the optical phase, which is very sensitive to GD and GD changes in a fibre, such provision is particularly important for this method.

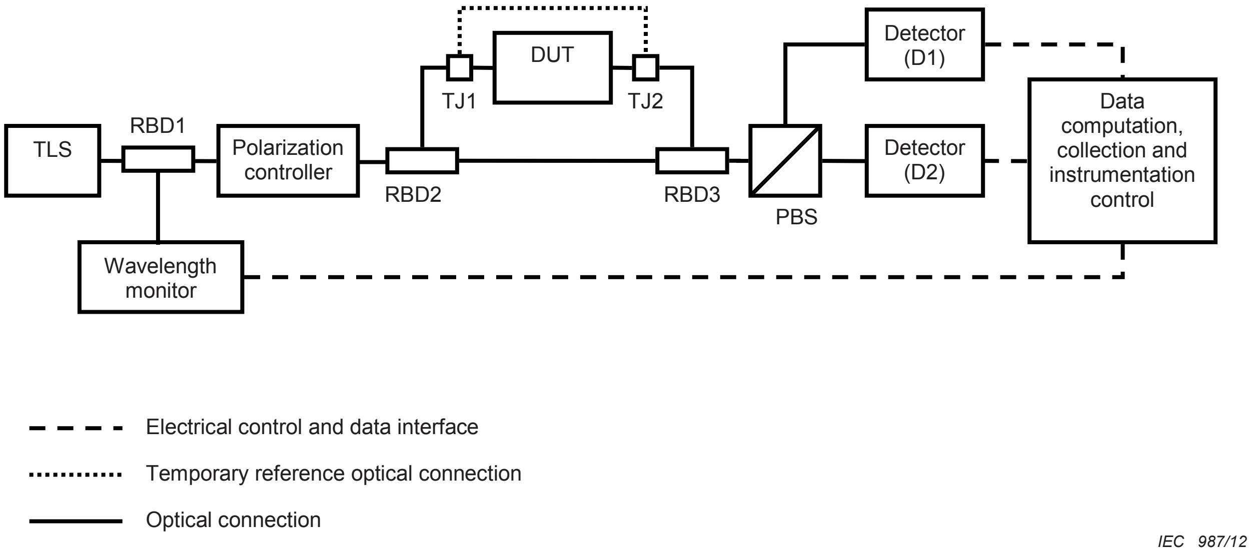

Figure 2 – SWI measurement method apparatus

5.2.2 Tunable laser source TLS

The SWI method uses coherent interference, so a tunable laser source is necessary to provide the variable wavelength signal. The TLS must be tunable across the required wavelength range. Considering typical coherence and wavelength resolution requirements, the line-width shall be less than 1 MHz. A typical device length of about 10m, including patch cords, will give an interferogram period of about 20 MHz. Accurate characterization of this requires a substantially smaller resolution. Typically closely spaced measurements are required (depending on the length and GD range of the DUT as discussed in 6.2.1), so it is highly recommended to perform the measurements during continuous wavelength scanning by the source. Therefore the setup shall provide specified control and monitoring of the wavelength while sweeping.

5.2.3 Wavelength monitor

If the TLS does not itself provide adequate wavelength accuracy, this shall be achieved with the wavelength monitor. The monitor improves absolute wavelength accuracy and relative wavelength accuracy for each measurement point during the wavelength scan.

5.2.4 Reference branching devices RBD1, RBD2, RBD3

The branching devices, RBD2 and RBD3, are used to establish the interferometer by splitting the optical path so that part of the light passes through the DUT and the other part passes along a reference path. The light from the two paths is then recombined so that it interferes at the detectors. These couplers will typically have a 50:50 coupling ratio. Further branching devices may be used to tap light for monitoring, as for the wavelength monitor. These should be selected to provide adequate signal for the monitoring function. The branching devices have 1×2 or 2×2 configuration. Unused ports of the RBD shall be terminated to give less than -50 dB back-reflection.

5.2.5 Detectors D1, D2

The detectors are used to trace the optical power with respect to wavelength. As described below, the recommended configuration produces two such traces for light at two orthogonal polarization states. The traces will generally yield oscillations in power with very short wavelength period as explained in 5.2.1, so that a high density of measurements vs. wavelength will be required. Therefore a high-speed data acquisition detection system is recommended. The discussion below assumes that the output signal corresponds to optical power. Since relative changes in power will be evaluated, the detectors should have good linearity, and care should be taken to avoid approaching saturation.

5.2.6 Polarization controller

To obtain sufficient interference signal from the interferometer, it must be assured that light from the two paths combines with the same polarization, since signals with orthogonal polarization will not produce interference. Since in general the polarization state of the light at the DUT output will be unknown, some control of the polarization is required. The polarization controller and polarization analyzer of 5.2.6 combine to satisfy this function, as described in Clause 5. Generally the polarization controller is used to establish the polarization at the DUT input and to “balance” the power at the two detectors from the reference path of the interferometer. The polarization controller shall be able to provide satisfactory polarization stability over the wavelength range of the measurement, for example by using zero-order retarding plates. The combination of polarization controller and analyzer also permits the calculation of DGD from a set of GD measurements at different polarization conditions.

5.2.7 Polarization analyzer

The polarization analyzer is the second part of the configuration to assure favourable interference conditions, based on polarization. A practical realization is to use the polarising beam splitter (PBS) in combination with the two detectors. When the polarization controller of 4.2.5 assures that similar power from the reference arm is present at both detectors, then the light from the DUT will also be split into two respective components with the same polarization at the detector as the reference light. This assures a good interference signal.

5.3 Polarization phase shift method

5.3.1 General

Figure 3 shows a block diagram of the polarization phase shift method (PPS). A detailed explanation of the various components of this system and their functions is contained in 5.3.2 to 5.3.8.

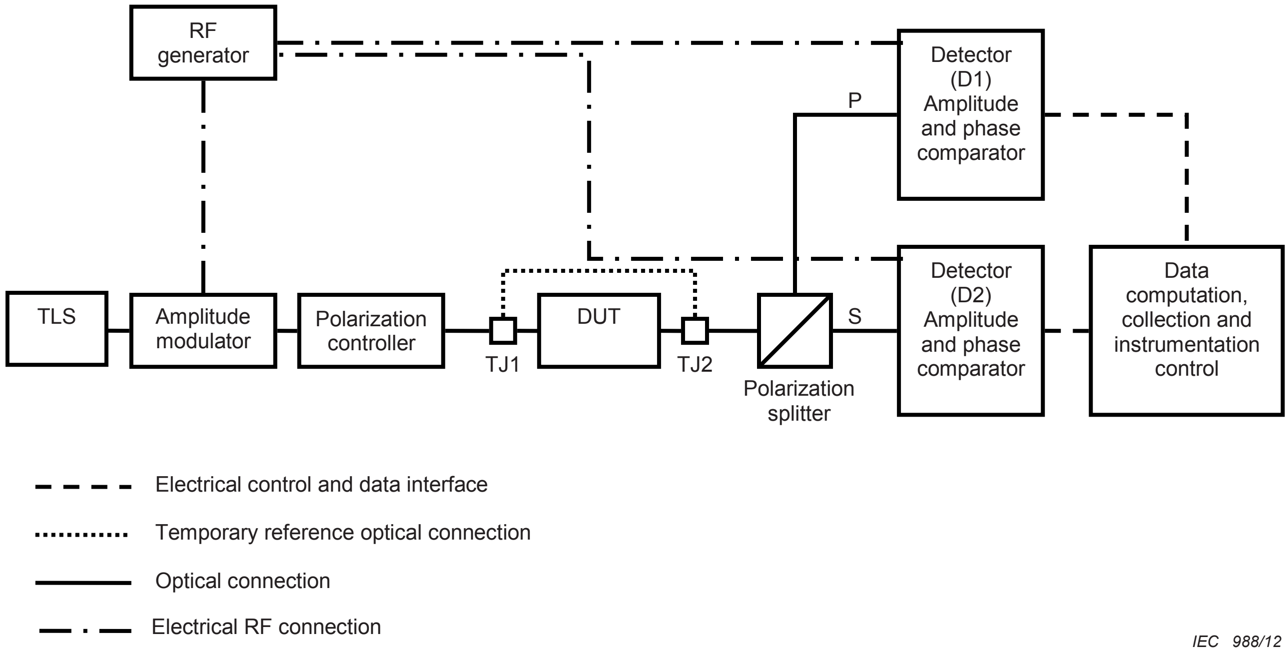

Figure 3 – PPS measurement method apparatus

5.3.2 Tunable laser source TLS

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 to be measured. To obtain a good SNR and wavelength resolution of the measurement result, the laser should have sufficient power for the required signal-to-noise ratio (SNR) of the result and the spectral line width should be narrow enough for the required wavelength resolution. 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 fibre.

The wavelength increment of the VWS shall be optimized for the period of the group delay ripple (GDR) of the DUT.

5.3.3 RF generator

The RF generator 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 50 MHz to 3 GHz. 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 optical spectrum spread. The effective wavelength resolution, $\Delta\lambda$ (nm), is restricted by the sidebands, and is generally given as:

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

where

λ is wavelength (nm)

f is the modulation frequency (GHz), and

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

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

$$\Delta \mathrm{GD} = \frac{\Delta \phi \times 10^3}{2\pi f} \quad (2)$$

where

$\Delta\phi$ is phase resolution of the phase comparator (radians)

f is modulation frequency (GHz)

5.3.4 Amplitude modulator

The optical intensity modulator modulates the intensity of light from the tunable laser source synchronized to the modulated pattern from RF signal source. The optical performances such as insertion loss, on-off extinction ratio and polarization extinction ratio shall satisfy the required value over the wavelength range to be measured. In order to achieve these performances, generally a $LiNbO_3$ (LN) modulator is used. A polarization maintaining fibre is used as an input fibre in order to connect with a tunable laser source. A driving voltage is generally determined from the half-wavelength voltage ($V\pi$) of the LN modulator, and the output power of the RF signal source is adjusted so that the degree of optical intensity modulation will be approximately 20 %.

5.3.5 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 shall be less than ± 0,1 degree and the polarization extinction ratio shall be more than 20 dB over the wavelength range to be measured.

5.3.6 Polarization splitter

The polarization splitter is placed after the DUT. The output light is separated into two orthogonally polarized signals, P- and S-polarised lights. Each signal is led to the optical detectors. The polarization splitter consists of a non-isotropic crystal such as a calcite prism possessing a high polarization extinction ratio of more than 20 dB. The insertion loss shall be less than 1 dB. The optical performances such as polarization extinction ratio and insertion loss of the polarization splitter shall satisfy the required value over the wavelength range to be measured.

5.3.7 Detectors D1, D2

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 $pA/(Hz)^{1/2}$, is generally used. The PIN photodiode must have response characteristics sufficient to respond to the modulation frequency of the RF signal source. In addition, to ensure a high signal to noise ratio, a broadband and low noise amplifier shall be used after the optical detectors.

5.3.8 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 tau (ps) is calculated from the phase using the following equation:

$$\tau = \frac{\phi \times 10^3}{2\pi f} \tag{3}$$

where

ϕ is phase (radians) and

f is the 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. The total phase accuracy including the frequency stability of the RF signal source shall be less than ± 0,3 degree or sufficient to ensure adequate measurement precision.

6 Measurement procedure

6.1 Modulation phase shift method

6.1.1 Measurement principle

GD, τ_g, is defined as the derivative of the optical phase Φ_{opt} with respect to its angular frequency $\omega_{opt} = 2\pi f_{opt}$ according to

$$\tau_g(\omega_0) = \left.\frac{d\Phi_{opt}(\omega_{opt})}{d\omega_{opt}}\right|_{\omega_0} = \left.\frac{1}{2\pi}\frac{d\Phi_{opt}(f_{opt})}{df_{opt}}\right|_{\nu_0} \tag{4}$$

In the MPS method, a wavelength tunable source is modulated in amplitude with a sinusoidal waveform at a radio (RF) /microwave frequency f_{RF}, typically in a range of 100 MHz to 3 GHz. The modulated optical signal is transmitted to the device under test and detected in the receiver. The phases of the RF signal relative to the reference modulation source φ_{RF1}, φ_{RF2}, ... φ_{RFn} are recorded at wavelengths λ_1, λ_2, ... λ_n corresponding to optical frequencies f_{opt1}, f_{opt2}, ... f_{optn}. These measurements are used to determine relative group delay, that is the change in group delay over a wavelength interval. From measurements of the RF phases at two adjacent wavelengths λ_i to λ_j, the change in GD, $\Delta\tau_g(\lambda_i,\lambda_j)$ can be obtained as

$$\Delta\tau_g(\lambda_i, \lambda_j) = \frac{\varphi_{RF}(\lambda_j) - \varphi_{RF}(\lambda_i)}{2\pi f_{RF}} \tag{5}$$

6.1.2 RF modulation frequency

The RF modulation frequency has to be selected carefully. A trade-off has to be made between GD noise on the measurement trace and the spectral resolution of the curve. Table 1 displays recommended maximum RF modulation frequencies for a certain required spectral resolution.

Particular attention should be paid to the relation between wavelength sample spacing and the modulation frequency. In particular, for devices showing high dispersion, the GD difference over the wavelength sample spacing limits the maximum modulation frequency that can be used without risking phase shifts of more than 180 degrees, which lead to ambiguous results due to phase-wrap errors. The modulation frequency should satisfy

$$f_{RF} < \frac{1}{\Delta\tau max} \qquad (6)$$

where $\Delta\tau_{max}$ is the maximum GD difference over the sampling spacing.

In the case where the spectral resolution due to modulation is equivalent to the wavelength sample, the measurements acquired at successive wavelengths can be averaged to synthesize (i.e. to give a result similar to the use of) a higher value of f_{RF}, because the phase contributions from the upper side-band of one acquisition are cancelled by the equal but opposite phase contributions of lower side-band of an adjacent acquisition.

Figure 4 illustrates an example case of three acquisition points where the wavelength sample spacing is equal to the modulation frequency. Each ellipse depicts the optical spectrum at each wavelength snapshot. As described above, the three successive snapshots can be averaged resulting in a single equivalent snapshot with an effective modulation frequency equal to $3f_{RF}$ and an effective central wavelength equal to λ_2 (i.e. mean of (λ_1, λ_2, λ_3)).

Table 1 – Modulation frequency versus wavelength resolution for C-band

Modulation Frequency (GHz)	**Wavelength resolution** (pm)
0,1	1,6
0,2	3,2
0,3	4,8
0,5	8,0
1,0	16,0
2,0	32,1
3,0	48,1

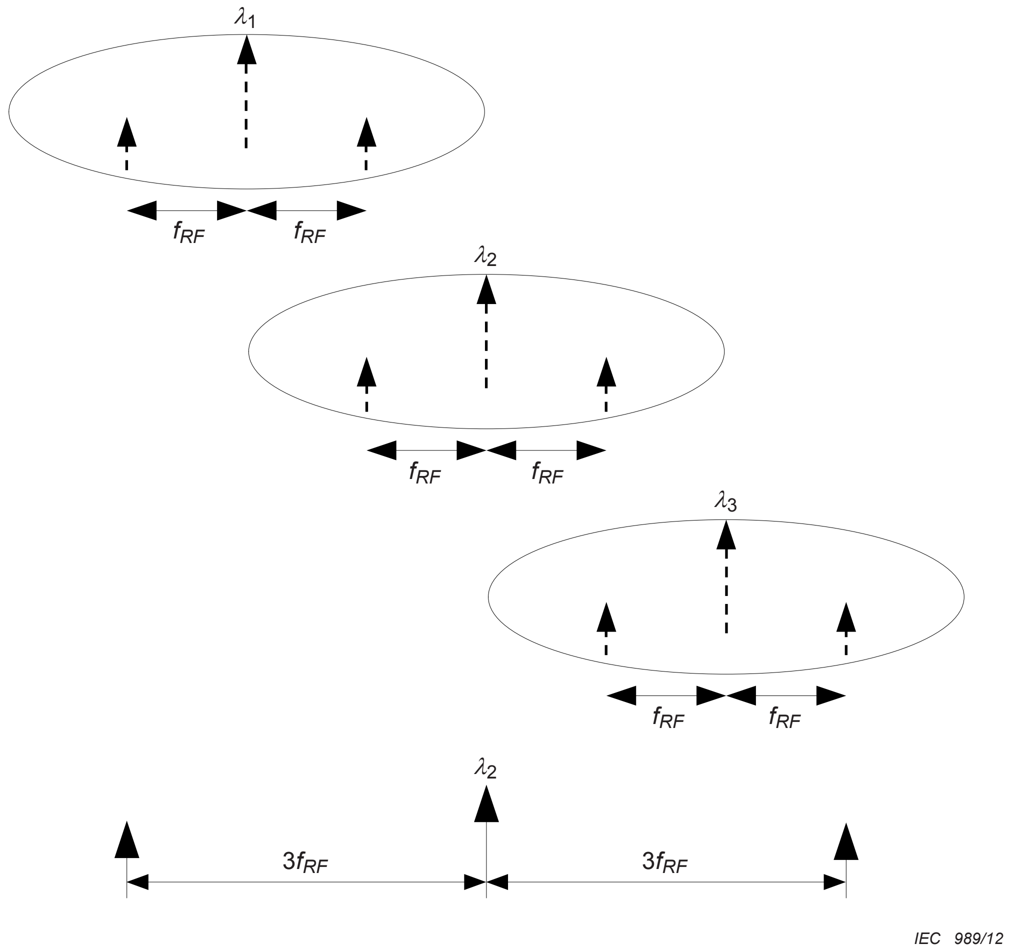

Figure 4 – Sampling at the modulation frequency

6.1.3 Test sequence

Using the setup shown in Figure 1, follow these steps:

(1) A sinusoidal waveform is generated by an RF generator. The frequency f_{RF} is typically selected in a range of 100MHz to 3GHz. This sinusoidal waveform will be used to drive the amplitude modulator and to synchronise phase detector D1 and D2. Optionally, the frequency f_{RF} is selected to be related to the wavelength sample spacing such that consecutive samples overlap as shown in figure 4.

(2) Optionally, the polarization controller is adjusted to be at 0º linear polarization. The actual orientation of this polarization is arbitrary, but usually refers to the state generated in the polarization controller. Further SOP are referenced to this one in Step 7.

(3) With no DUT attached, connect a fibre patch-cord between TJ1 and TJ2. Scan the wavelength of the TLS, recording the wavelengths and phases from D1 and D2 for points with the selected wavelength sample spacing. The results are an array of values (λ_i, $\varphi_{Ref}(D1)_i$, $\varphi_{Ref}(D2)_i$). This provides a “zero-loss” reference for normalizing the phase of the DUT signal.

(4) Attach the DUT at TJ1 and TJ2. Scan the wavelength of the TLS, recording the wavelengths and phases from D1 and D2 for points with the selected wavelength sample spacing. The results are an array of values (λ_i, $\varphi_{DUT}(D1)_i$, $\varphi_{DUT}(D2)_i$). This provides a phase of the DUT signal.

(5) Steps 3 and 4 can be repeated individually to reduce random noise in the phase measurements by “averaging” the multiple scans.

(6) Optionally, as described in 6.1.2, if the modulation frequency f_{RF} is equal to the wavelength sample spacing, a boxcar smoothing can be applied to achieve the measurements as if it were acquired at higher modulation frequencies.

(7) As an optional but recommended extension, steps 3 to 6 can be duplicated with the polarization controller at 45° and 90° linear polarization states, and the fourth state on the pole of the Poincaré sphere for circular polarization. This allows determination of the GD average over all input states of polarization.

6.1.4 Special notice for measurement of GDR

The wavelength resolution shall be chosen carefully to optimize for the period of group delay ripple (GDR) of DUT. The wider wavelength resolution reduces the group delay noise but degrades ability to resolve group delay ripple due to smoothing.

6.1.5 Calculation of relative group delay

In 6.1.3, step 3 and step 4 provide a "zero-loss" reference and the phase measurements of the DUT signal. The relative GD at the wavelength λ_i can be calculated as shown

$$\tau_g(\lambda_i) = \frac{(\varphi_{DUT}(D2)_i - \varphi_{Ref}(D2)_i) - (\varphi_{DUT}(D1)_i - \varphi_{Ref}(D1)_i)}{2\pi f_{RF}} 10^{12} \quad (7)$$

where φ is the phase in radians, f_{RF} is the modulation frequency in Hz and GD is in ps.

6.2 Swept wavelength interferometry method

6.2.1 Measurement principle

This method uses an optical interferometer and a tunable coherent light source to measure the dependence on wavelength of the optical phase of the light, φ, transferred by the DUT. The absolute GD is then calculated according to its definition as the derivative of phase with respect to optical frequency,

$$GD = \frac{d\varphi}{d\omega} \quad (8)$$

Here the phase φ refers to the phase of the optical (electromagnetic) wave, and ω is the optical frequency, expressed in rad/s. For example, the electrical field strength of light propagating in vacuum in the x-direction could be expressed as

$$E(x,t) = E_0 \cos\left(2\pi\left(\frac{x}{\lambda}\right) - \omega t\right) \quad (9)$$

where the argument of the cosine function is the phase, φ, and the amplitude of the field E_0 is proportional to the square root of the optical power.

Note that this method is different to Method D of IEC 60793-1-42, called "interferometry", for measuring the CD of optical fibres, in which a low-coherence light source is used. In that Method D, it is the length of the reference arm of the interferometer that is varied to match the optical length of the arm including the DUT. That method is not appropriate for measuring components like filters requiring high wavelength resolution, because a broadband light source is needed to provide good resolution of GD.

The interferometer measures the relative change vs. wavelength in the phase of the light from the DUT with respect to the light through the reference path. When the phase is such that the light combines constructively, the power is higher at the detector than when only light from the reference path is present. When the light combines destructively, the power is lower.

Generally the power level will oscillate as the wavelength is scanned, because the phase advances at different rates in the two paths as the wavelength is changed, if they have different optical length. The greater the path length difference, the more rapidly the detected power changes with wavelength. The period of the oscillation, $\Delta\lambda$ is given by

$$\Delta\lambda = \lambda^2 / \Delta L \quad (10)$$

where ΔL is the optical path length difference. Note that for a difference of 1 m, this gives a period of only 2,4 pm. If the difference is 10 m, then the period is only 0,24 pm. Thus it can be seen that a setup flexible enough to measure different devices without reconfiguration should be able to measure with a wavelength resolution smaller than 0,1 pm.

After recording the trace of power vs. wavelength, the interferogram, the dependence of phase on optical frequency can be extracted, which then allows calculating the absolute GD. The GD is then also a function of frequency or wavelength.

6.2.2 Test sequence

Using the setup shown in Figure 2, follow these steps:

(1) With no DUT attached, so that TJ1 and TJ2 are not connected, adjust the polarization controller to obtain equal power at D1 and D2. This establishes the first input state of polarization. It is recommended to make this adjustment with the TLS set to the middle of the wavelength range to be measured. Directivity should be better than 50 dB for the branching device.

(2) Attach the DUT at TJ1 and TJ2. The reflectance spectrum of the DUT can also be measured, for instance by using a 2 x 2 coupler at RBD2 and attaching TJ2 to the additional port on the left side of RBD2. For measurements with low uncertainty, it is best to wait a few minutes after attaching for the temperature and position of the fibre pigtails to stabilize.

(3) Scan the wavelength of the TLS, recording the wavelengths and signals from D1 and D2, for points with spacing 0,1 pm or smaller, as required by the length of the DUT. The result is an array of values (λ_i, $P1_i$, $P2_i$).

(4) Optionally, a normalization measurement with a fibre patch-cord between TJ1 and TJ2 can also be made. This provides a “zero-loss” reference for normalizing the amplitude of the DUT signal, allowing accurate measurement of the attenuation. This measurement also produces an array of values (λ_i, $N1_i$, $N2_i$), where N is the power trace from each detector.

(5) Steps 3 and 4 can be repeated to reduce random noise in the spectra by “averaging” the multiple scans. Because it is not desired to smooth out the interference oscillations in this process however, the averaging should be performed with the results of analysis on the raw data arrays of steps 3 and 4.

(6) As an optional but recommended extension, steps 2 to 5 can be duplicated for the second polarization state adjusted to the orthogonal state compared with the first polarization state, using the polarization controller. This allows determination of the GD averaged over all input states of polarization and of the DGD.

6.2.3 Special notice for measurement of GDR

The wavelength resolution shall be chosen carefully to optimize for the period of group delay ripple (GDR) of DUT. The wider wavelength resolution reduces the group delay noise but degrades ability to resolve group delay ripple due to smoothing.

6.2.4 Calculation of group delay

The result of step 3 above actually yields two interferograms, given by the arrays (λ_i, $P1_i$) and (λ_i $P2_i$). (Including the results of step 6, there are four such interferograms in total.) These are separately processed in the same way in the following calculations. Each will yield a GD spectrum, which may differ if the DUT has non-zero DGD.

The interferogram, which is here expressed in terms of $\omega = 2\pi c / \lambda$ as $P(\omega)$, has values

$$P(\omega) = R(\omega) + D(\omega) + 2\sqrt{R(\omega)}\sqrt{D(\omega)}\cos(\varphi(\omega)) \tag{11}$$

where R is the power at the detector from the reference path, D is the power at the detector from the DUT and φ is the optical phase difference between the two optical paths. All of these are functions of ω. To obtain the third term of this equation with the phase information, the interferogram $P(\omega)$ is high-pass filtered. The cut-off of the high-pass filtering can be estimated by using a Fourier transform to identify the interferogram frequencies related to the GD of the device. The Hilbert transform of this term is then used to obtain the ω-dependent values of amplitude and phase:

$$2\sqrt{R(\omega)}\sqrt{D(\omega)} \text{ and } \varphi(\omega)\text{, respectively.} \tag{12}$$

These arrays can then be averaged over repeated wavelength scans if required, as mentioned in step 5 of 6.2.2. The high number of data points can now also be reduced to the desired wavelength resolution, using boxcar averaging.

The GD is now obtained as:

$$\mathrm{GD}\left(\frac{\omega_{i+1} + \omega_i}{2}\right) = \frac{\varphi(\omega_{i+1}) - \varphi(\omega_i)}{\omega_{i+1} - \omega_i} \tag{13}$$

This calculation is performed for the interferograms of both detectors and the results are averaged to form the polarization-averaged GD spectrum for this input polarization state, which may then be expressed as a function of ω or λ. The fully averaged GD spectrum is obtained by also averaging the results for GD obtained from the same analysis on the results of step 6. Note that, given a zero length reference measurement, the GD values are absolute and indicate the length of the device.

The insertion loss of the DUT can also be determined from these data, after performing a similar analysis on the normalization results of step 4 to obtain $2\sqrt{R(\omega)}\sqrt{D_N(\omega)}$ as the amplitude from the Hilbert transform of the corresponding $N(\omega)$ data. Then the polarization-averaged transfer T_{ave} of the DUT is given by

$$T_{ave}(\omega) = \sum \frac{R(\omega)D(\omega)}{R(\omega)D_N(\omega)} \tag{14}$$

where the summation is over values from the two, or four if step 6 is used, polarization-resolved interferograms.

The average insertion loss of the device is then given by the average of this from the interferograms of both detectors, expressed in dB.

$$\mathrm{IL}(\omega) = -10\,log(T_{ave}(\omega)) \tag{15}$$

6.3 Polarization phase shift method

6.3.1 Modulation frequency

The modulation frequency shall be chosen based on the required wavelength resolution and GD or CD noise. For more information, refer to 6.3.2.

The wavelength resolution shall be chosen carefully to optimize for the period of group delay ripple (GDR) of DUT. The wider wavelength resolution reduces the group delay noise but degrades ability to resolve group delay ripple due to smoothing.

6.3.2 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 difference, $\Delta\tau_{max}$ that can be measured between the adjoining wavelengths is given by the following expression.

$$\Delta\tau_{max} \le \left| \pm \frac{180}{360} \times \frac{10^3}{f} \right| = \frac{10^3}{2f} \tag{16}$$

This wavelength increment, $\Delta\lambda$, will be called wavelength step size. To measure up to a certain value, the wavelength step size is decided as follows.

$$\Delta\lambda \le \left| \pm \frac{\Delta\tau_{max}}{CD_{max}} \right| \tag{17}$$

where

$\Delta\lambda$ is wavelength step size (nm),

$\Delta\tau_{max}$ is the maximum GD of the DUT in ps,

f is the modulation frequency in GHz, and

CD_{max} is the maximum CD to be measured in ps/nm.

The minimum increment of wavelength of VWS shall be chosen to optimize for the period of the group delay ripple (GDR) of DUT.

6.3.3 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 ($d\varphi_{11}/d\omega_{mea}$ and $d\varphi_{21}/d\omega_{mea}$, respectively) for the 0-degree linearly polarized wave are measured. 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 ($d\varphi_{12}/d\omega_{mea}$ and $d\varphi_{22}/d\omega_{mea}$) are measured.

6.3.4 Calibration

A calibration is performed on a single-mode fibre whose length is less than 1 m before the 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. 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 6.3.5.

6.3.5 Calculation of relative group delay and CD

The P- and S-polarized light GDs are calculated using measured values from 6.3.3 and 6.3.4.

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: $\frac{d\Phi_{ave1}}{d\omega} = \left(\frac{d\Phi_{11}}{d\omega} + \frac{d\Phi_{12}}{d\omega}\right) \Big/ 2$

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 (18)

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

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

$GD_{average}$ that does not depend on polarization: $GD(\lambda) = \left(\frac{d\Phi_{ave1}}{d\omega} + \frac{d\Phi_{ave2}}{d\omega}\right) \Big/ 2$ (19)

$CD_{average}$ that does not depend on polarization: $CD(\lambda) = \frac{(GD(\lambda + \Delta\lambda) - GD(\lambda - \Delta\lambda))}{2 \times \Delta\lambda}$

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

6.4 Measurement window (common for all test methods)

The spectral width of the measurement window is typically given in the specification of the DUT. Generally, the measurement window is defined in two different ways. First, the measurement window is centred on an ITU wavelength with a defined width. For example, the GD is required to be analysed within a 25 GHz optical BW centred on the ITU frequency as shown in Figure 5 for a multiple channel DUT. Each channel is plotted against the corresponding ITU frequency.

Secondly, it also may be required to analyse the dispersion properties of the DUT in a measurement window that is defined by the loss properties of the DUT. For example, the DUT is a filter with a wavelength dependent loss as given in Figure 6. The dispersion measurement will be carried out afterwards in a window that ranges from λ_1 to λ_2. λ_1 and λ_2 are given by the minus x dB points of the loss curve. Typical values for x are in the range 0,5 dB to 5 dB.

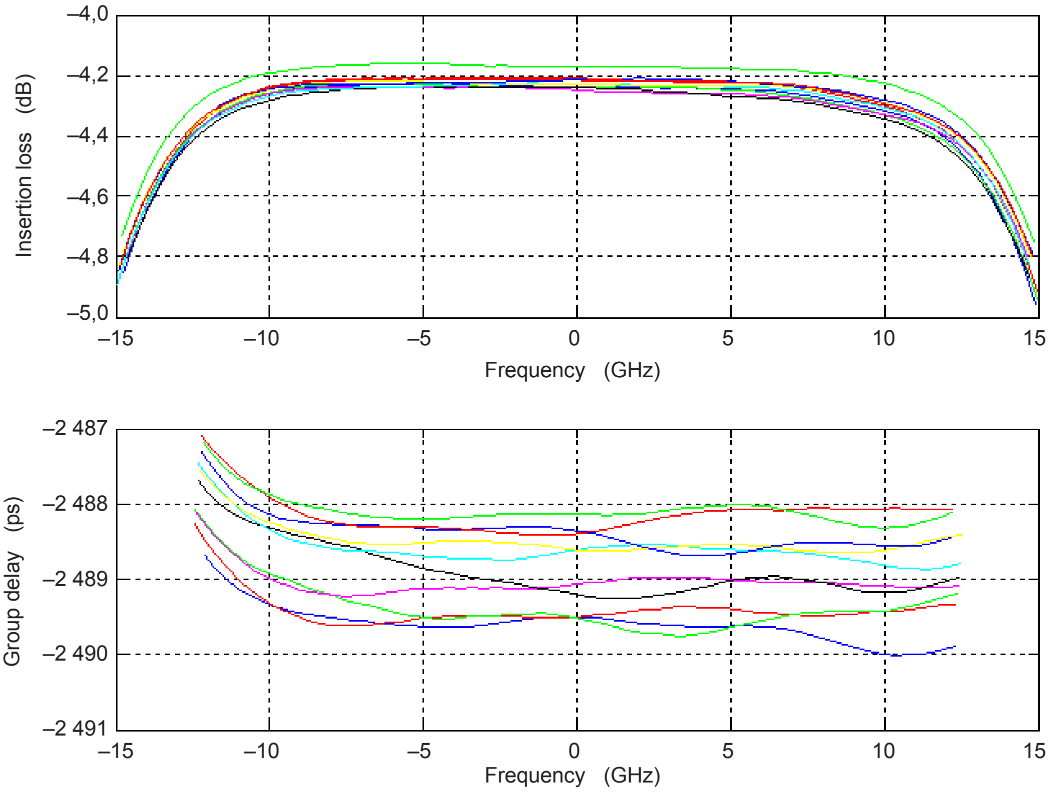

Figure 5 – Measurement window centred on an ITU wavelength with a defined width

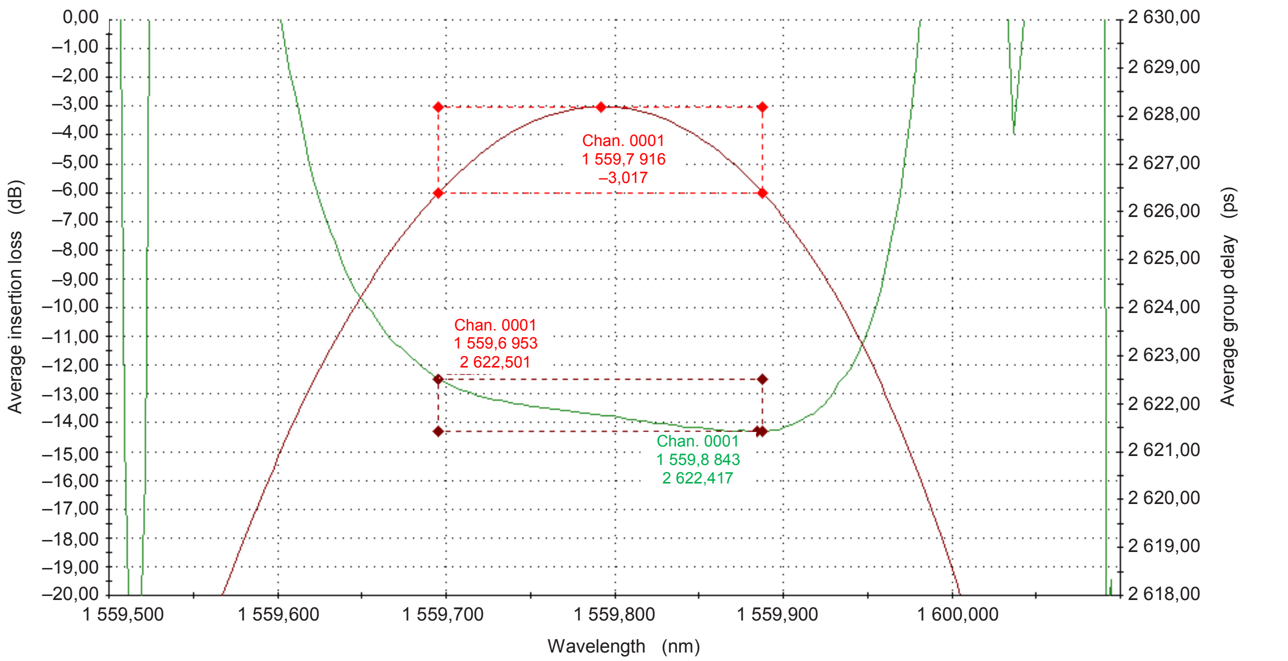

Figure 6 – Measurement window determined by the insertion loss curve at 3dB

7 Analysis

7.1 Noise reduction of group delay measurement

7.1.1 Averaging

Multiple measurements of the phase difference between the reference signal and the detected optical signal may be averaged. If the noise is non-deterministic the noise level will decrease by the square root of the number of averages. Averaging does not sacrifice the wavelength resolution, but has a time trade-off.

7.1.2 Spectral filtering

Filter methods may be applied for reducing the measurement noise. The most commonly applied filter is averaging over a defined spectral window. Where DWDM components are being characterized typical widths of such windows are 5 to 10 pm. Broadband components may allow window widths of up to 1 nm and more. It has to be taken into account that the optical signal is spectrally broadened due to the RF modulation and therefore already provides a spectrally averaged measurement value. For these reasons it is required to state the applied RF frequency and the width of the spectral filtering window in the measurement protocol.

For DWDM components, when averaging over a spectral region, multiple measurement points over a spectral window are averaged. This delivers smoother measurement curves by reducing the spectral resolution. Particular care has to be taken not to average out relevant details of the measurement.

7.2 Linear phase variation

If the phase response of a linear phase system is strictly linear, it will cause a delay, but no distortion. Any deviation from linearity within the BW of the signal will distort the signal.

The linear phase system is expressed as

$$\phi(f_{\mathrm{opt}}) = \phi(f_{\mathrm{opt0}}) + 2\pi\tau_{\mathrm{g}}(f_{\mathrm{opt}} - f_{\mathrm{opt0}}) \qquad (20)$$

where the GD τ_g is a constant. For most components, a linear fit to the phase is performed, and then this linear curve is subtracted from the original phase. The remaining phase value is the departure from linear phase.

7.3 Chromatic dispersion

7.3.1 General

It is well known that CD is the derivative of the GD as a function of wavelength.

$$\mathrm{CD}(\lambda) = \frac{\mathrm{d}\tau_{\mathrm{g}}(\lambda)}{\mathrm{d}\lambda} \qquad (21)$$

However, in practice, this derivative must be performed numerically.

$$\mathrm{CD}(\lambda_{\mathrm{i}}) = \frac{\tau_{\mathrm{g}}(\lambda_{\mathrm{i+1}}) - \tau_{\mathrm{g}}(\lambda_{\mathrm{i-1}})}{\lambda_{\mathrm{i+1}} - \lambda_{\mathrm{i-1}}} \qquad (22)$$

where i = 1,2, ... , n. $\Delta\lambda = \lambda_{i+1} - \lambda_i = \lambda_i - \lambda_{I-1}$ represents the wavelength sample spacing. If the wavelength sample spacing $\Delta\lambda$ is relatively small, the GD noise will be amplified in the CD calculation. There are many ways to minimise the calculated CD noise. Normally, two methods are recommended.

7.3.2 Finite difference calculation

The spectral filtering (or averaging) method is applied to reduce the GD noise before performing the CD calculation. It is normally applied for narrow band devices. The number of measurement points filtered (or averaged) over a spectral window depends on the CD noise improvement, avoiding averaging out relevant details of the measurement and not distorting the processed GD curve.

7.3.3 Curve fit

A curve is fitted, by least mean squares procedure, to the GD data over a measurement window defined in 5.1.5. CD is calculated from the differentiation of the fitted GD curve with respect to wavelength in order to reduce the GD noise. It is normally applied to a broadband device, i.e. a long spool of fibre. However, if the GD variation is relatively smooth in the measurement window, this method can also apply for the narrow band device. One example of a multiple channel DUT is shown in Figure 7. CD is processed in the following ways for each channel.

1) A 6th order polynomial curve is fitted, by least mean squares procedure, to group delay data over a 25 GHz optical BW centred on the ITU frequency as shown in Figure 8.
2) The offset frequency, in GHz, from the ITU grid frequency is used for the frequency axis to minimize decimal place requirements for good fit. The fit is within ±0,5 ps of the raw data.
3) CD is calculated from the differentiation of the fitted GD curve with respect to wavelength. The wavelength step used for calculation is 6 pm.

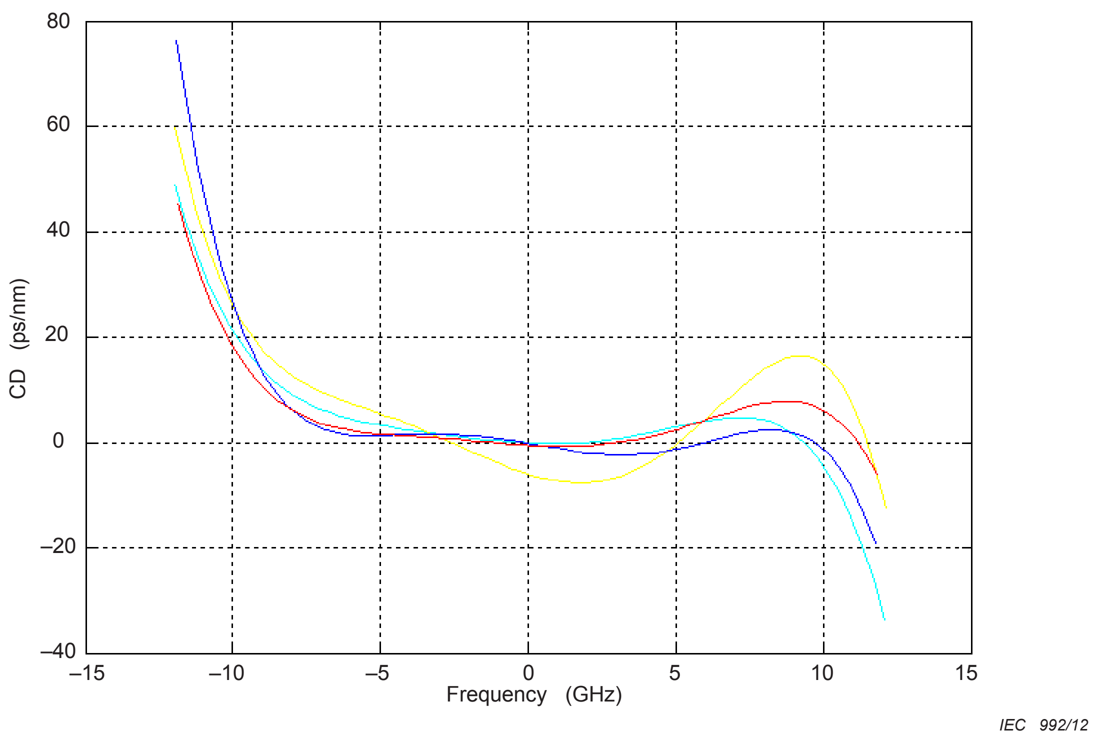

Figure 7 – Calculated CD from fitted GD over a 25 GHz optical BW centred on the ITU frequency

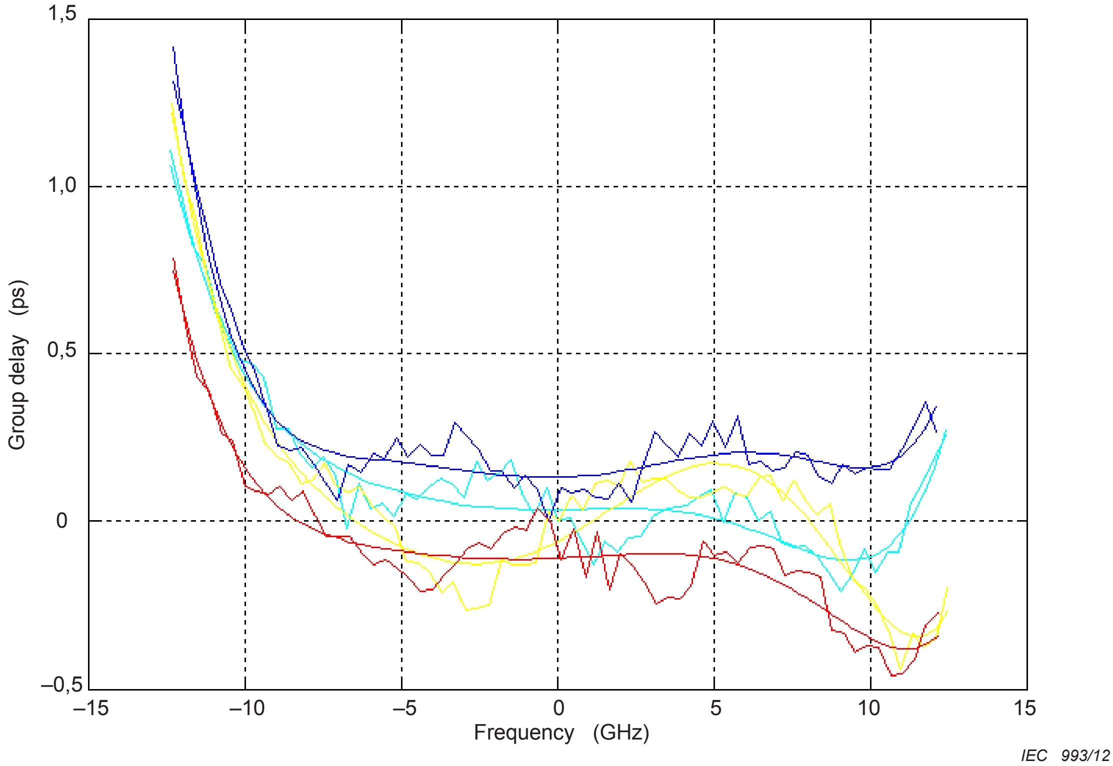

Figure 8 – A 6th order polynomial curve is fitted to relative GD data over a 25 GHz optical BW centred on the ITU frequency

7.4 Phase ripple

7.4.1 General

The method of estimating the phase ripple from the measurement data of GD is shown below. This is only valid for DWDM dispersion compensators.

7.4.2 Slope fitting

Calculate linear-fit value of group delay measurement results for the bandwidth specified in the DUT specifications (unless otherwise specified, the 3 dB bandwidth of the insertion loss characteristics), using least-square method and get the deviation between linear and group delay. These values contain group delay ripples.

7.4.3 GDR estimation

Determine the amplitude and period of the group delay ripple using the above result. The amplitude should be determined over two cycles of the group delay ripple. The maximum amplitude in the measurement range should be chosen as the peak-to-peak group delay ripple. The period should be chosen as the average over several cycles including the maximum amplitude. Determine the period based on the crossings of the mean value of group delay for each ripple. Figure 9 shows an example of GDR estimation. This only works if the GDR is plotted against frequency.

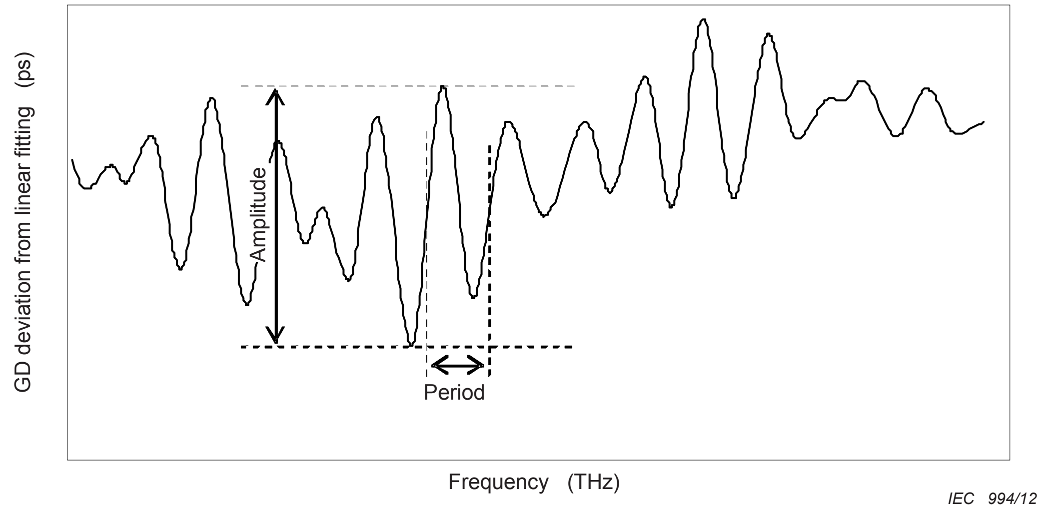

Figure 9 – Estimation of the amplitude of the GD ripple and the period

7.4.4 Phase ripple calculation

Calculate peak-to-peak phase ripple ($\Delta\theta$) from group delay ripple using following equation.

$$\Delta\theta = f_{period} * A_{rip} \text{ (unit: radians)} \tag{23}$$

where,

A_{rip} peak-to-peak group delay ripple (unit: s)

f_{period} period of the group delay ripple (unit: Hz).

8 Examples of measurement

8.1 50GHz band-pass thin-film filter

Example results for the GD and IL spectra of a 50 GHz band- pass thin-film filter are shown in Figure 10.

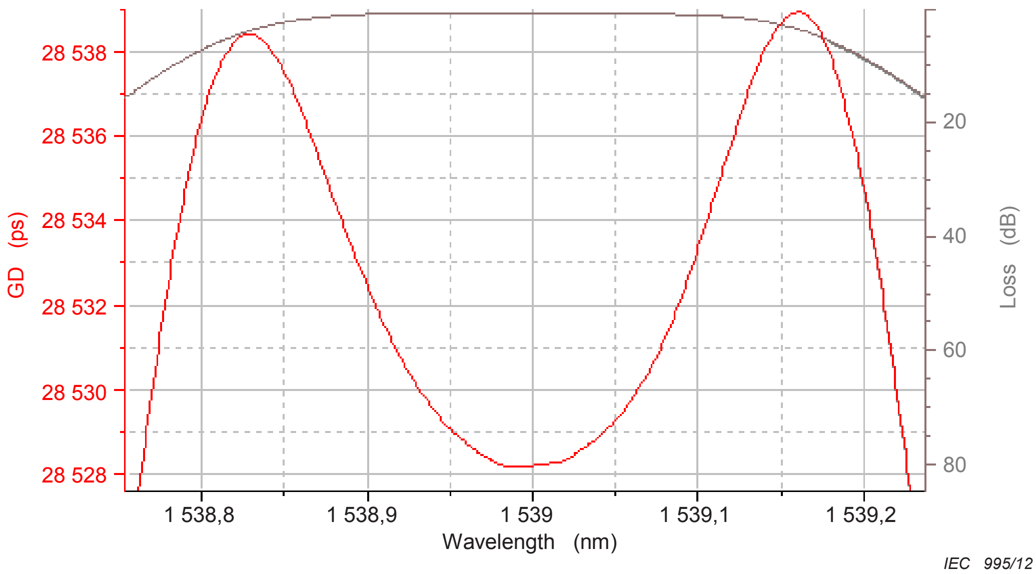

Figure 10 – GD and loss spectra for a 50 GHz-channel-spacing DWDM filter

8.2 Planar waveguide filter component

Figures 11 and 12 show the examples of GD and CD measurement for a planar waveguide filter component.

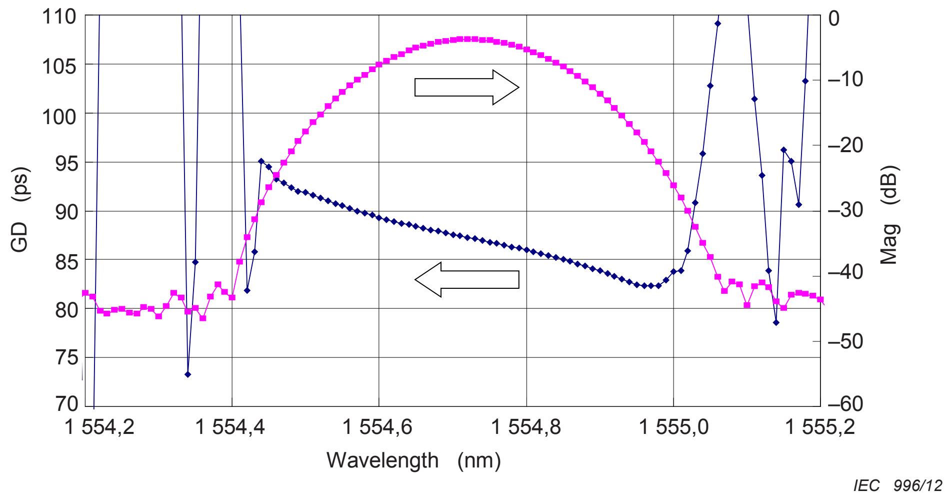

Figure 11 – Measured GD and loss spectra for planar waveguide filter

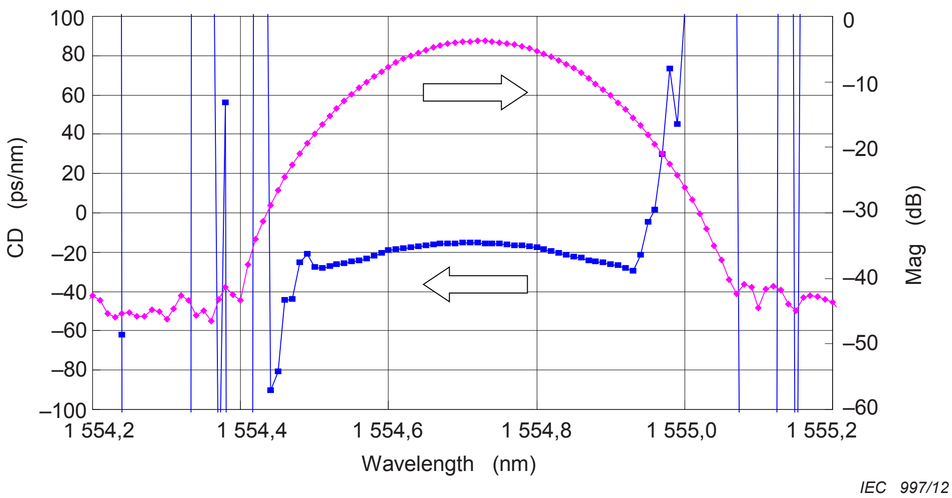

Figure 12 – Measured CD and loss spectra for planar waveguide filter

8.3 Tunable dispersion compensator (fiber bragg grating)

Figures 13 and 14 show the examples of GD deviation from linear fitting and phase ripple measurement for a fibre Bragg grating using Polarization average MPS method. The modulation frequency f_{RF} is 500 MHz.

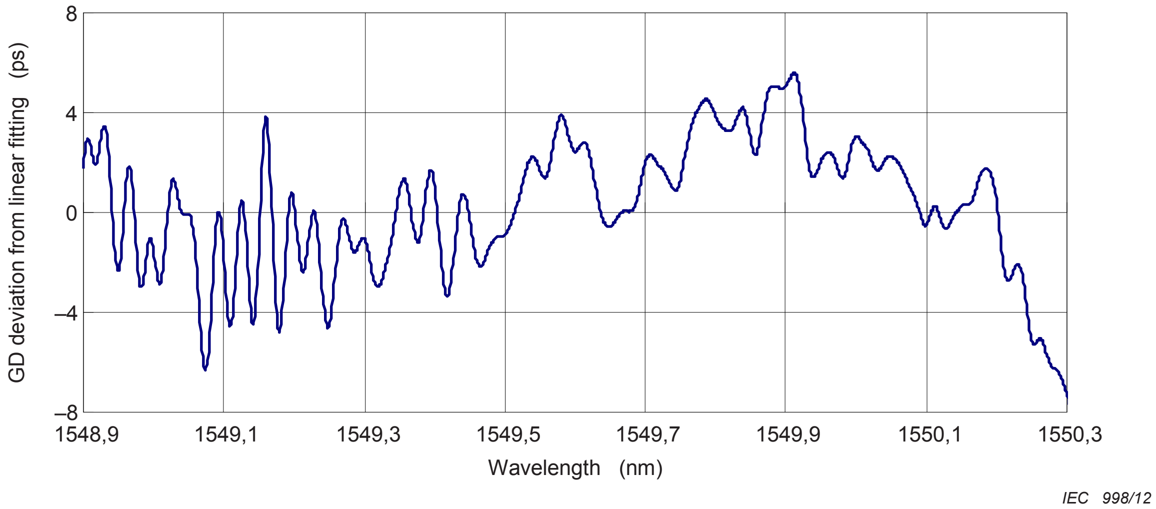

Figure 13 – Measured GD deviation of a fibre Bragg grating

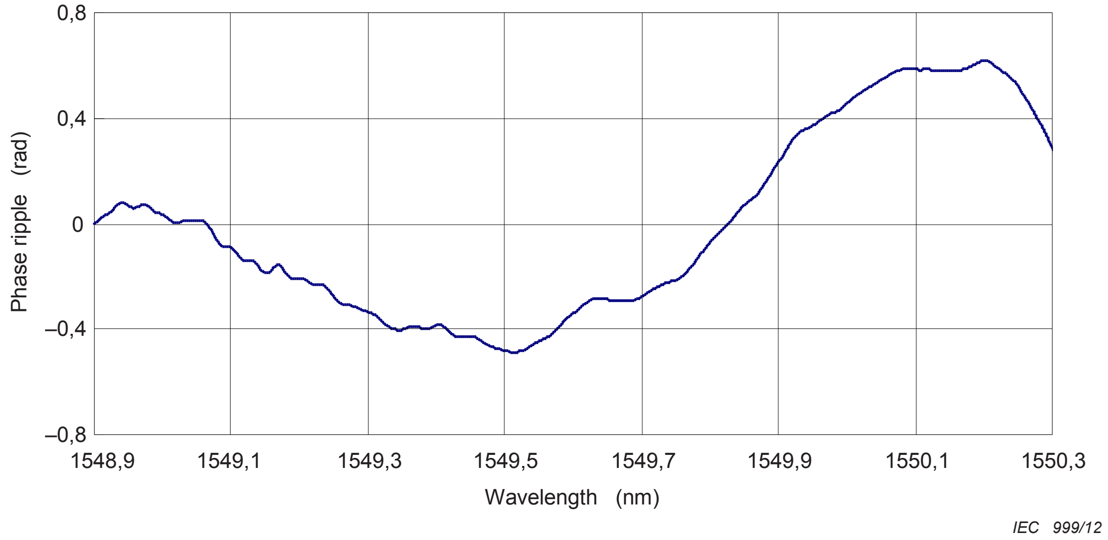

Figure 14 – Measured phase ripple of a fibre Bragg grating

8.4 Random polarization mode coupling device

Figure 15 shows a GD measurement example for a device with random polarization mode coupling, showing the advantage of averaging GD over the polarization states. Without averaging, the GD curve can vary by one half of the DGD.

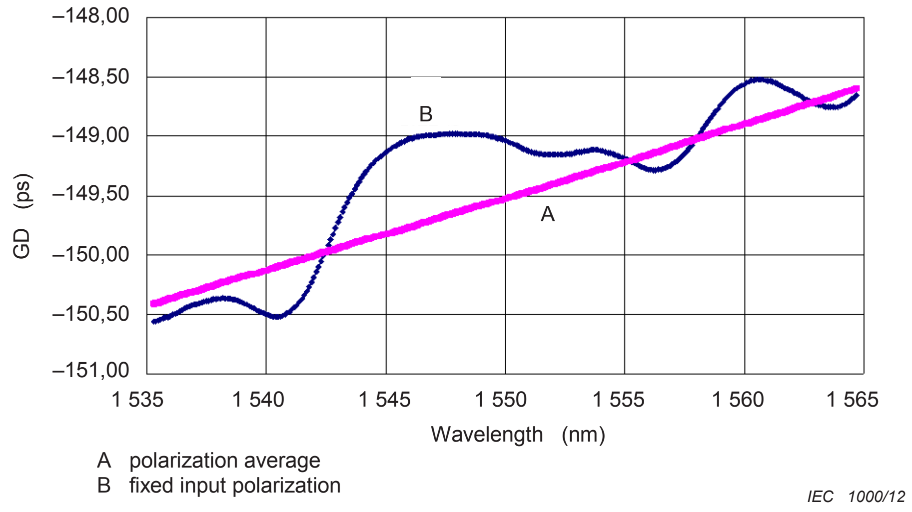

Figure 15 – Measured GD for a device with random polarization mode coupling

Figure 16 shows a CD measurement example for a device with random polarization mode coupling.

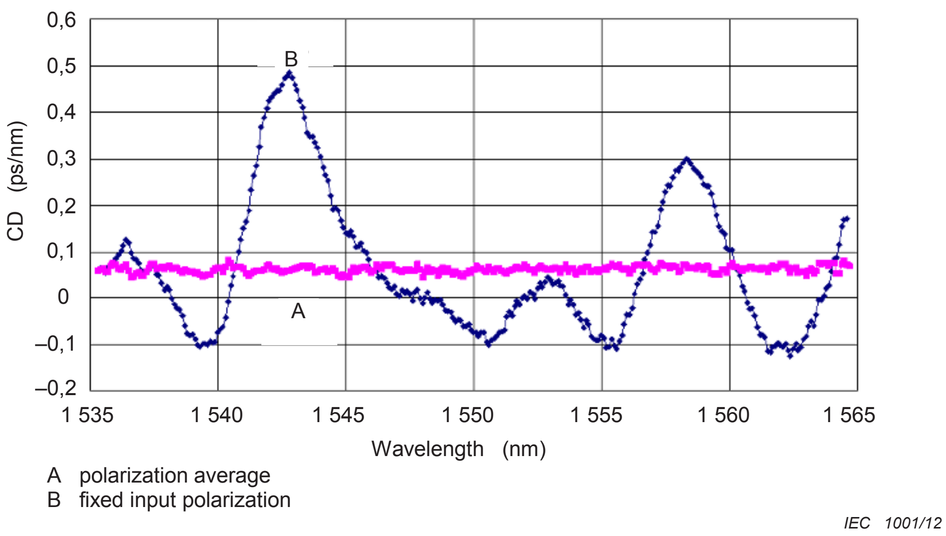

Figure 16 – Measured CD for a device with random polarization mode coupling

9 Details to be specified

The following details shall be specified.

- Measurement uncertainty
- Test method used
- Wavelength range
- Wavelength accuracy
- Wavelength resolution
- Environmental characteristics (T, P, H)
- RF modulation frequency
- Number of averages of phase measurement
- Spectral averaging window

Annex A
(informative)

Calculation of differential group delay

A.1 General

The methods of this standard use polarized light sources. For the measurement of components exhibiting polarization dependence, which is often the case, the measurement should be performed for a sufficient set of input polarizations to assure determination of the polarization-average GD spectrum, as described in 6.1. Such a procedure also provides sufficient measured data to determine the DGD spectrum, DGD(λ), as described in this Annex. The intention of this Annex is to support the simultaneous measurement of GD and DGD with the same measurement apparatus. Methods dedicated specifically to DGD or PMD are described in IEC 61300-3-32 and IEC 61282-9.

A.2 Calculation of DGD from measurements made with the MPS method at 4 states of input polarization

This method requires repeating steps 3 to 6 of 6.1.3 for four different input states of polarization, chosen to a Mueller set of input SOPs. A Mueller set of input SOPs is most easily described on the Poincaré sphere, as shown in figure A.1.

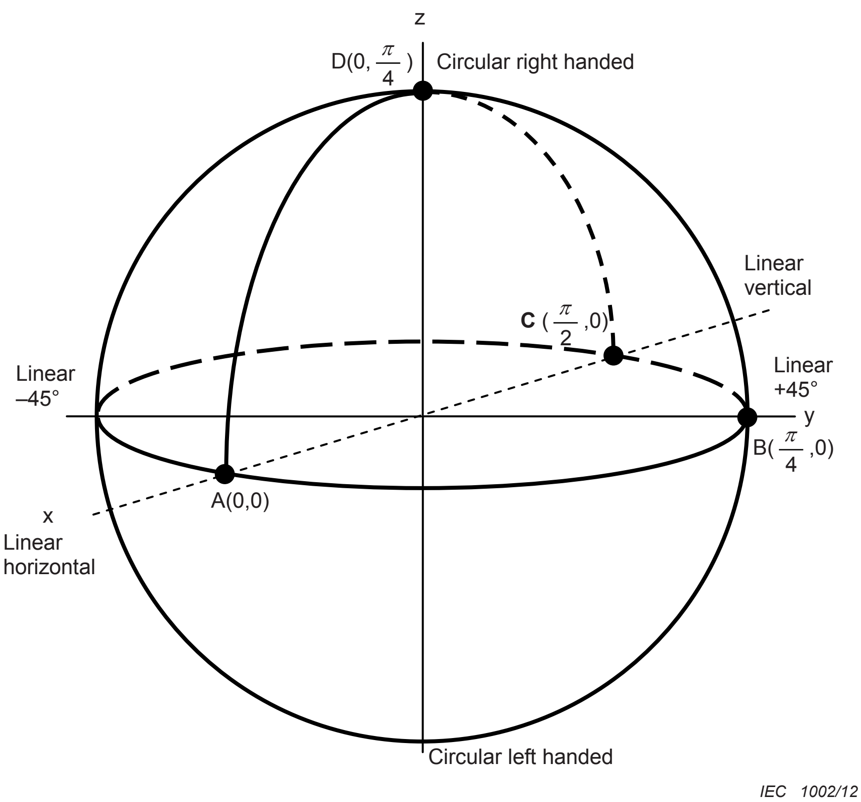

Figure A.1 – Mueller states on Poincaré sphere

SOPs that are orthogonal are 180° apart on the Poincaré sphere. Three of the SOPs are on a great circle of the sphere and are inter-mutually separated by 90°, as illustrated in figure A.1. Using the right hand rule relative to the "north pole", starting at an arbitrary point, A, on the great circle, positions B and C follow by successively adding 90°. Position D is orthogonal to the other points and oriented “up” using the right hand rule. The following spherical co-ordinate system describes the normalised input Stokes vector, s_0, the parameters of which are used to define an example of a Mueller set where the great circle is on the equator. The parameter, θ, is the linear orientation of the associated normalised Jones vector, j_0. The parameter, μ, is the phase difference of the x and y elements of that vector.

$$s_0 = \begin{bmatrix} \cos 2\theta \\ \sin 2\theta \cos \mu \\ \sin 2\theta \sin \mu \end{bmatrix} \qquad j_0 = \begin{bmatrix} \cos\theta \exp[-j\mu/2] \\ \sin\theta \exp[j\mu/2] \end{bmatrix} \tag{A.1}$$

Table A.1 shows the example of Mueller set.

Table A.1 – Example of Mueller set

Position	θ	μ	Description
A	0	0	Linear polarization @ 0° (horizontal)
B	$\pi/4$	0	Linear polarization @ 45° (45°)
C	$\pi/2$	0	Linear polarization @ 90° (vertical)
D	$\pi/4$	$\pi/2$	Circular polarization (spherical)

For each, position, A, B, C, and D, measure the phase shifts (radians), designated, $\phi_A(\lambda)$, $\phi_B(\lambda)$, $\phi_C(\lambda)$, $\phi_D(\lambda)$, respectively, as in 6.1.3.

Calculate the average phase of the two PSPs, $\phi_{RF}(\lambda)$, as:

$$\phi_{RF}(\lambda) = \frac{\phi_A(\lambda) + \phi_C(\lambda)}{2} \tag{A.2}$$

Adjust the measured phase values by the average phase as:

$$\begin{aligned} \phi_{RF,A}(\lambda) &= \phi_A(\lambda) - \phi_{RF}(\lambda) \\ \phi_{RF,B}(\lambda) &= \phi_B(\lambda) - \phi_{RF}(\lambda) \\ \phi_{RF,D}(\lambda) &= \phi_D(\lambda) - \phi_{RF}(\lambda) \end{aligned} \tag{A.3}$$

Calculate the phase difference, $\delta_{RF}(\lambda)$, as:

$$\delta_{RF}(\lambda) = 2\arctan\left\{\left[\tan^2\left(\phi_{RF,A}(\lambda)\right) + \tan^2\left(\phi_{RF,B}(\lambda)\right) + \tan^2\left(\phi_{RF,D}(\lambda)\right)\right]^{1/2}\right\} \tag{A.4}$$

The DGD (ps) is calculated using $\delta_{RF}(\lambda)$ (radians) and the modulation frequency, f, (GHz) as:

$$\mathrm{DGD}(\lambda) = 10^3 \frac{\delta_{RF}(\lambda)}{2\pi f} \tag{A.5}$$

A.3 Calculation of DGD from measurements made with the MPS method while scanning the states of input polarization, “all states method”

This measurement may be made by scanning the state of input polarization with the polarization controller of Figure 1, while fixing the VWS at fixed wavelength steps, and measuring the relative GD for a large set of SOP. The DGD, expressed in units of ps, is determined as the difference between the maximum and minimum GD values at a particular wavelength.

To obtain the desired accuracy, it is necessary to assure that the set of SOP is sufficiently large, by scanning at a sufficiently fast rate or for a long enough time, and sufficiently polarization-resolved, by averaging the individual samples over sufficiently short time with respect to the polarization scanning rate.

An improvement in the noise level and thus accuracy of the DGD determination can be obtained by evaluating the complete distribution of GD samples over the SOP, instead of basing the determination only on the two values of maximum and minimum GD in the set. When the state of input polarization is scanned in a random manner, there is a simple relationship between the standard deviation of the distribution of GD values and the range between the minimum and maximum values. As can be seen for instance by regarding the representation of the SOP on the surface of the Poincaré sphere, the density of polarization states with respect to the difference between the components of the polarization along two orthogonal states of polarization is constant. When these two orthogonal states are chosen to be the two principal states of polarization, PSP, of the component, this means there is a constant density of polarization states versus measured GD, over the range from minimum to maximum GD. Therefore the size of this range can be obtained from the standard deviation of the GD samples according to the equation:

$$\mathrm{DGD} = \mathrm{GD}_{max} - \mathrm{GD}_{min} = 2\sqrt{3}\sigma \tag{A.6}$$

where σ is the standard deviation of the GD samples.

A.4 Calculation of DGD from measurements made with the SWI method

The SWI method described in 5.2, including the measurement at two orthogonal input states of polarization described in step 6 of 6.2.2, provides the amplitude and phase of the component's transfer matrix elements for two orthogonal input and output states of polarization. The wavelength dependence of this matrix can be used to calculate DGD according to the Jones Matrix Eigenanalysis, JME,

The transfer matrix, T(ω), for this purpose is assembled in the following manner. From the ω-dependent values of amplitude and phase for the two output states of polarization at the first input state of polarization, the complex matrix elements T_{11} and T_{21} are computed from the results of 6.2.4 according to:

$$T_{11}(\omega) = \frac{\sqrt{D_{11}(\omega)}}{\sqrt{D_{N11}(\omega)}} \mathrm{Exp}\left(j\,\phi_{11}(\omega)\right) \text{ and } T_{21}(\omega) = \frac{\sqrt{D_{21}(\omega)}}{\sqrt{D_{N21}(\omega)}} \mathrm{Exp}\left(j\,\phi_{21}(\omega)\right) \tag{A.7}$$

Similarly from the results for the second input state of polarization, the complex matrix elements T_{12} and T_{22} are computed according to:

$$T_{12}(\omega) = \frac{\sqrt{D_{12}(\omega)}}{\sqrt{D_{N12}(\omega)}} \mathrm{Exp}\left(j(\phi_{12}(\omega)+\pi)\right) \text{ and } T_{22}(\omega) = \frac{\sqrt{D_{22}(\omega)}}{\sqrt{D_{N22}(\omega)}} \mathrm{Exp}\left(j\,\phi_{22}(\omega)\right) \tag{A.8}$$

Note that the phase of T_{12} is reversed here with the offset of π, because the phase relationship from the reference arm of the interferometer at the two detectors is reversed for the second input state with respect to the first, when the setup of Fig. 2 is used.

These elements are then combined to form the matrix T(ω):

$$\vec{T} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \quad \text{(A.9)}$$

Next the eigenvalues, ρ_1 and ρ_2, are found for $T(\omega_{n+1})T^{-1}(\omega_n)$, where ω_n and ω_{n+1} are the optical frequency for adjacent points in the measured spectra. The DGD values, $\Delta\tau$, averaged respectively over the interval from ω_n to ω_{n+1}, are given for each interval by:

$$\Delta\tau = \left| \frac{\mathrm{Arg}\left(\rho_1 / \rho_2 \right)}{\omega_{n+1} - \omega_n} \right| \quad \text{(A.10)}$$

where Arg() denotes the argument function, such that $\mathrm{Arg}(ae^{i\varphi})=\varphi$. In this way, the DGD spectrum can be generated for the measured range. An example is shown in Figure A.2 for the same device as in Figure 10.

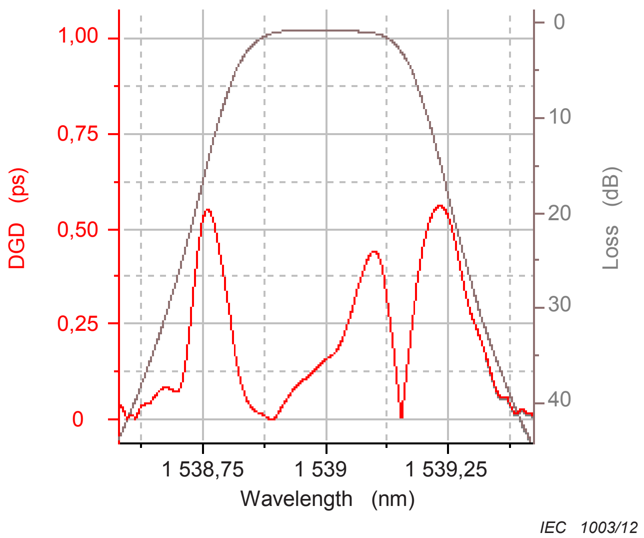

Figure A.2 – DGD spectrum for a 50 GHz bandpass filter, measured with 30 pm resolution BW

A.5 Calculation of DGD from measurements made with the PPS method

The PPS method is described in 5.3 and 6.3. The following parameters are calculated using measured values in 6.3.3 and 6.3.4.

$$\begin{aligned}
\overline{\alpha}_1 &= \frac{\Delta\Theta}{\Delta\omega} = \frac{\Delta\Theta}{2\pi c \cdot \delta\lambda} \cdot \lambda_i \lambda_f \\
\overline{\beta}_1 &= \frac{1}{4}\left(\frac{d\Phi_{11}}{d\omega} - \frac{d\Phi_{22}}{d\omega} - \frac{d\Phi_{21}}{d\omega} + \frac{d\Phi_{12}}{d\omega}\right) \\
\overline{\gamma}_1 &= \frac{1}{4}\left(\frac{d\Phi_{11}}{d\omega} - \frac{d\Phi_{22}}{d\omega} + \frac{d\Phi_{21}}{d\omega} - \frac{d\Phi_{12}}{d\omega}\right) \\
\Theta &= \frac{1}{2}\cos^{-1}\left(\frac{|T_{11}|^2 - |T_{21}|^2}{|T_{11}|^2 + |T_{21}|^2}\right) \\
\cos 2\Theta_0 &= \frac{|T_{11}|^2 - |T_{21}|^2}{|T_{11}|^2 + |T_{21}|^2}
\end{aligned} \tag{A.11}$$

where

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

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

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

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

$$DGD(\lambda) = 2\sqrt{\overline{\alpha}_1^2 + \overline{\beta}_1^2 + \overline{\gamma}_1^2 + 2\overline{\beta}_1\overline{\gamma}_1 \cos 2\Theta_0} \tag{A.13}$$

The calculation technique can result in a series DGD values versus wavelength. Figures A.3 and A.4 show examples of such characteristics.

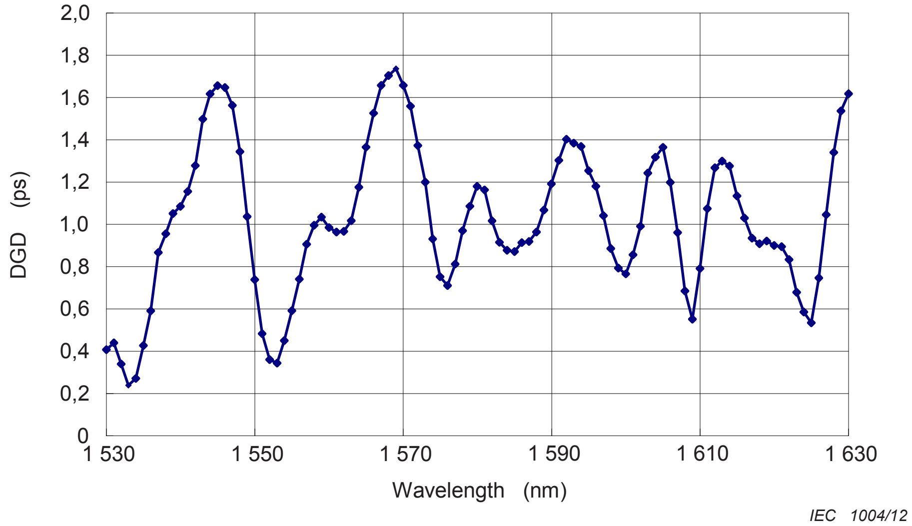

Figure A.3 – DGD versus wavelength for a random polarization mode coupling device (example)

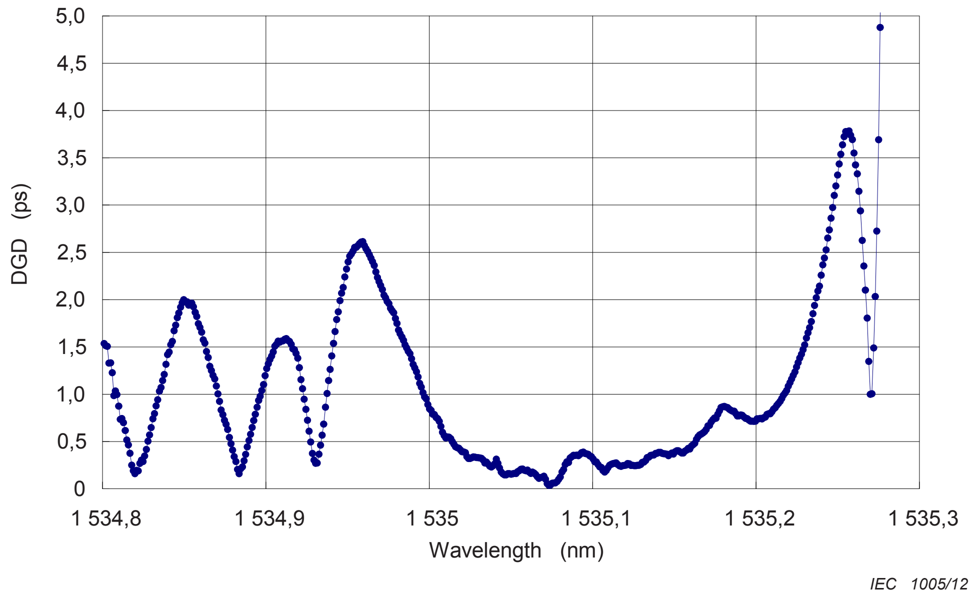

Figure A.4 – DGD versus wavelength for a fibre Bragg grating filter (example)

The derivation of DGD concerning this method is described here, and is similar to the Jones Matrix Eigenanalysis method. The optical transfer function matrix can be expressed as:

$$\begin{aligned} T(\omega) &= \begin{bmatrix} |T_{11}| \times \exp(-j\,\Phi_{11}) & |T_{12}| \times \exp(-j\,\Phi_{12}) \\ |T_{21}| \times \exp(-j\,\Phi_{21}) & |T_{22}| \times \exp(-j\,\Phi_{22}) \end{bmatrix} \\ &= \begin{bmatrix} \cos\Theta \times \exp(-j\,\phi - j\,\psi) & -\sin\Theta \times \exp(-j\,\phi + j\,\psi) \\ \sin\Theta \times \exp(+j\,\phi - j\,\psi) & \cos\Theta \times \exp(+j\,\phi + j\,\psi) \end{bmatrix} \times \exp(-j\,\Phi) \end{aligned} \qquad \text{(A.14)}$$

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

$$E^{out}(\omega) = T(\omega) \times E^{in}(\omega) \qquad \text{(A.15)}$$

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:

$$E^{out}(\omega) = E^{out}(\omega_0) + \left.\frac{dE^{out}}{d\omega}\right|_{\omega=\omega_0} \delta\omega + \frac{1}{2}\left.\frac{d^2E^{out}}{d\omega^2}\right|_{\omega=\omega_0} \delta\omega^2 \qquad \text{(A.16)}$$

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

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

$$D(\omega) = \frac{dT(\omega)}{d\omega} \times T(\omega)^{-1} \quad (A.17)$$

Therefore, the following expression is obtained by substituting A9 for A8.

$$\begin{aligned} E^{out}(\omega) &= \left\{1 + D\delta\omega + \frac{1}{2}D^2\delta\omega^2 + \frac{1}{2}\frac{dD}{d\omega}\delta\omega^2\right\} \times E^{out}(\omega_0) \\ &\cong \exp\left\{D\delta\omega + \frac{1}{2}\frac{dD}{d\omega}\delta\omega^2\right\} \times E^{out}(\omega_0) \end{aligned} \quad (A.18)$$

where the high order term is negligible. D(ω) is the first order PMD operator and dD(ω)/dω is the second order PMD operator. They are not commutative with each other.

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

$$\begin{aligned} X^{-1} \times E^{out}(\omega) &= X^{-1}\exp(D \times \delta\omega) X \times X^{-1}E^{out}(\omega_0) \\ &= \begin{bmatrix} \exp(-j\Gamma_+ \times \delta\omega) & 0 \\ 0 & \exp(-j\Gamma_- \times \delta\omega) \end{bmatrix} \times X^{-1}E^{out}(\omega_0) \end{aligned} \quad (A.19)$$

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

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

Four independent parameters Θ, ϕ, ψ and Φ described in expression A.14 make the following expression using Taylor expansion.

$$\begin{aligned} \Theta &= \Theta_0 + \bar{\alpha}_1\delta\omega + \frac{1}{2}\bar{\alpha}_2\delta\omega^2 \\ \phi &= \phi_0 + \bar{\beta}_1\delta\omega + \frac{1}{2}\bar{\beta}_2\delta\omega^2 \\ \psi &= \psi_0 + \bar{\gamma}_1\delta\omega + \frac{1}{2}\bar{\gamma}_2\delta\omega^2 \\ \Phi &= \Phi_0 + \beta_1\delta\omega + \frac{1}{2}\beta_2\delta\omega^2 \end{aligned} \quad (A.20)$$

Where

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

Θ_0, ϕ_0, ψ_0, Φ_0 the values of Θ, ϕ, ψ, Φ at $\omega - \omega_c = 0$

$\bar{\alpha}_1$, $\bar{\beta}_1$, $\bar{\gamma}_1$, 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(ω) is expressed using expression A.20 as:

$$D(\omega) = -j\beta_1\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - j\begin{bmatrix} \bar{\beta}_1 + \bar{\gamma}_1\cos 2\Theta & \left(-j\bar{\alpha}_1 + \bar{\gamma}_1\sin 2\Theta\right) \times e^{-j2\varphi} \\ \left(+j\bar{\alpha}_1 + \bar{\gamma}_1\sin 2\Theta\right) \times e^{+j2\varphi} & -\bar{\beta}_1 - \bar{\gamma}_1\cos 2\Theta \end{bmatrix} \quad (A.21)$$

Therefore, the eigenvalues of D(ω) are expressed as:

$$j\Gamma_{\pm} = -j\beta_1 \pm j\sqrt{\overline{\alpha}_1^{\,2} + \overline{\beta}_1^{\,2} + \overline{\gamma}_1^{\,2} + 2\overline{\beta}_1\overline{\gamma}_1 \cos 2\Theta} \qquad \text{(A.22)}$$

Where β_1 is the polarisation-independent group delay.

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

$$\Delta\tau = \Gamma_+ - \Gamma_- = 2\sqrt{\overline{\alpha}_1^{\,2} + \overline{\beta}_1^{\,2} + \overline{\gamma}_1^{\,2} + 2\overline{\beta}_1\overline{\gamma}_1 \cos 2\Theta} \qquad \text{(A.23)}$$

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

Bibliography

IEC 60793-1-42, *Optical fibres – Part 1-42: Measurement methods and test procedures – Chromatic dispersion*

IEC 61282-9*, Fibre optic communication system design guides – Part 9: Guidance on polarization mode dispersion measurements and theory*

IEC 61300-1, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 1: General and guidance*

IEC 61300-3-1, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 3-1: Examinations and measurements – Visual examination*

IEC 61300-3-32, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 3-32: Examinations and measurements – Polarization mode dispersion measurement for passive optical components*

IEC/TR 62343-6-3, *Dynamic Modules – Round robin measurement results for group delay ripple of tunable dispersion compensators*

Frederick W. King, *Hilbert Transforms: Volume 1 (Encyclopedia of Mathematics and its Applications)*

____

This page deliberately left blank

British Standards Institution (BSI)

BSI is the independent national body responsible for preparing British Standards and other standards-related publications, information and services. It presents the UK view on standards in Europe and at the international level.

BSI is incorporated by Royal Charter. British Standards and other standardisation products are published by BSI Standards Limited.

Revisions

British Standards and PASs are periodically updated by amendment or revision. Users of British Standards and PASs should make sure that they possess the latest amendments or editions.

It is the constant aim of BSI to improve the quality of our products and services. We would be grateful if anyone finding an inaccuracy or ambiguity while using British Standards would inform the Secretary of the technical committee responsible, the identity of which can be found on the inside front cover. Similary for PASs, please notify BSI Customer Services.

Tel: +44 (0)20 8996 9001 Fax: +44 (0)20 8996 7001

BSI offers BSI Subscribing Members an individual updating service called PLUS which ensures that subscribers automatically receive the latest editions of British Standards and PASs.

Tel: +44 (0)20 8996 7669 Fax: +44 (0)20 8996 7001
Email: plus@bsigroup.com

Buying standards

You may buy PDF and hard copy versions of standards directly using a credit card from the BSI Shop on the website **www.bsigroup.com/shop.** In addition all orders for BSI, international and foreign standards publications can be addressed to BSI Customer Services.

Tel: +44 (0)20 8996 9001 Fax: +44 (0)20 8996 7001
Email: orders@bsigroup.com

In response to orders for international standards, BSI will supply the British Standard implementation of the relevant international standard, unless otherwise requested.

Information on standards

BSI provides a wide range of information on national, European and international standards through its Knowledge Centre.

Tel: +44 (0)20 8996 7004 Fax: +44 (0)20 8996 7005
Email: knowledgecentre@bsigroup.com

BSI Subscribing Members are kept up to date with standards developments and receive substantial discounts on the purchase price of standards. For details of these and other benefits contact Membership Administration.

Tel: +44 (0)20 8996 7002 Fax: +44 (0)20 8996 7001
Email: membership@bsigroup.com

Information regarding online access to British Standards and PASs via British Standards Online can be found at **www.bsigroup.com/BSOL**

Further information about British Standards is available on the BSI website at **www.bsi-group.com/standards**

Copyright

All the data, software and documentation set out in all British Standards and other BSI publications are the property of and copyrighted by BSI, or some person or entity that own copyright in the information used (such as the international standardisation bodies) has formally licensed such information to BSI for commerical publication and use. Except as permitted under the Copyright, Designs and Patents Act 1988 no extract may be reproduced, stored in a retrieval system or transmitted in any form or by any means – electronic, photocopying, recording or otherwise – without prior written permission from BSI. This does not preclude the free use, in the course of implementing the standard, of necessary details such as symbols, and size, type or grade designations. If these details are to be used for any other purpose than implementation then the prior written permission of BSI must be obtained. Details and advice can be obtained from the Copyright & Licensing Department.

Tel: +44 (0)20 8996 7070
Email: copyright@bsigroup.com

BSI

389 Chiswick High Road London W4 4AL UK

Tel +44 (0)20 8996 9001
Fax +44 (0)20 8996 7001
www.bsigroup.com/standards

raising standards worldwide™