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2007-04

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

Part 3-38: Group delay and chromatic dispersion

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

Part 3-38: Group delay and chromatic dispersion

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The text of this PAS is based on the following document: This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document:

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

Part 3-38: Group delay and chromatic dispersion

1 Scope

The purpose of this PAS is to define the measurement methods necessary to characterize the group delay properties of passive components. From these measurements further parameters like group delay ripple, linear phase deviation, chromatic dispersion, and dispersion slope can be derived. In addition, when these measurements are made with resolved polarization, the differential group delay (DGD) can also be determined as an alternative to separate measurement with the dedicated methods of IEC 61300-3-32.

2 Normative references

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

IEC 60050-731:1991, *International Electrotechnical Vocabulary (IEV) – Chapter 731: Optical fibre communication*

IEC 60793-1-42:2001, *Optical fibres – Measurement methods and test procedures – Chromatic dispersion*

IEC/TR 61282-9:2006, *Fibre optic communication system design guides – Part 9: Guidance on polarization mode dispersion measurements and theory*

IEC 61300-3-29:2005, *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*

IEC 61300-3-2:2006, *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*

3 Terms, definitions and abbreviations

For the purposes of this document, many of the terms, definitions and abbreviations are described in IEC 60050-731 and IEC 61300-3-29; some terms, definitions and abbreviations specific to this measurement method are given below.

BW bandwidth: spectral width of a signal or filter

CD chromatic dispersion (in ps/nm): change of group delay over wavelength: CD = d(GD)/dλ

δ step size of the VWS during a swept measurement

λ_c centre channel or nominal operating wavelength for a component

RF frequency of electrical driving signal of intensity modulator

GD group delay: time required for a signal to propagate through a device

SSE source spontaneous emission: broadband emissions from a laser cavity that bear no phase relation to the cavity field. These emissions can be seen as the baseline noise on an optical spectrum analyser

SW spectral width: spectral width of a given filter in relation to the pass band (i.e. –25dB SW). It differs from BW in that it is always defined by the outermost crossings in the event that there are more than two

GDR group delay ripple

LPV linear phase variation

MPS modulation phase shift

Φ phase delay

f_{RF} modulation frequency

SWI swept wavelength interferometry

VWS variable wavelength source

DWDM dense wavelength division multiplexing

4 General description

This document covers transmission measurements of the group delay properties of passive components. In order to interpret the group delay properties, it is essential to have the amplitude spectral measurement also available. For this reason, loss measurements are also covered to the extent as it is 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.

The document will be separated into different sections, one concentrating on the measurement methods and the other on analysis of the measurement data.

The measurement methods covered in this document are the modulation phase shift method and the swept-wavelength interferometry 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.

5 Apparatus

5.1 Modulation phase method

The measurement set-up for the characterization of the GD properties of optical components is shown in Figure 1. A detailed explanation of the various components of this system and their functions is given below.

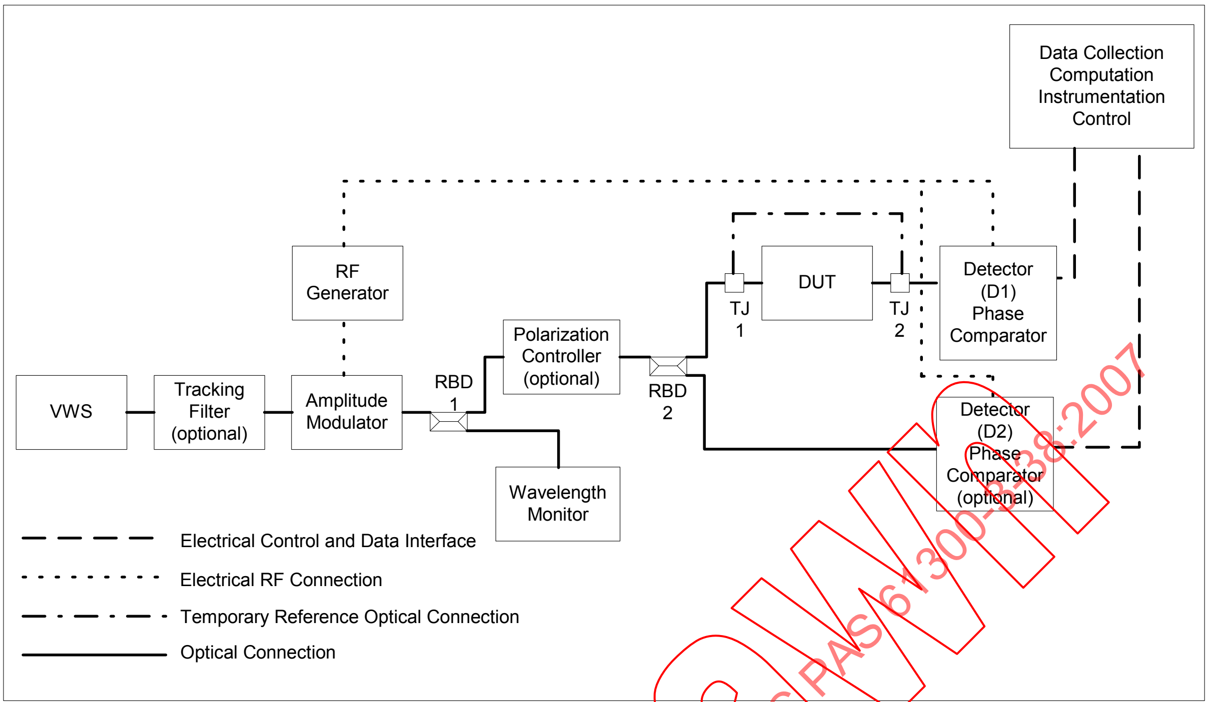

Figure 1 – MPS measurement method apparatus

5.1.1 Variable wavelength source

The VWS is a 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 better than the required accuracy of the amplitude measurements for insertion loss. 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. This accuracy may be obtained by having the wavelength monitor feedback to the VWS. The line width of the source shall be less than 100 MHz. The tuning range of the VWS shall cover the entire spectral region of the DWDM device and the source shall also be free of mode-hopping over that tuning range. The output power of the VWS shall be sufficient to provide the apparatus with an order of magnitude more dynamic range than the device exhibits (i.e. the measurement apparatus shall be able to measure a 50 dB notch filter if the device is a 40 dB notch).

5.1.2 Tracking filter

The tracking filter may be used for any notch filter measurements if the dynamic range of the VWS and the detector does not allow for measuring a depth of at least 40 dB due to the shape of the device under test (DUT) and the broadband SSE of the VWS. The filter must 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 dB to 50 dB dynamic range at the transmission detector.

5.1.3 Reference branching device (RBD1, 2)

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 back-reflection <-50dB. 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, if this is to be measured. The directivity shall be at least 10 dB higher than the maximum return loss, if this is to be measured. 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.

5.1.4 Wavelength monitor

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, the wavelength monitor shall be 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 2 ppm. 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 dB 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 dB of attenuation noise.

5.1.5 Device under test (DUT)

For the purposes of this document, the test ports shall be a single “input-output” path. The method described herein can be extrapolated upon to obtain a single measurement system capable of handling even an m × n device. The device shall be terminated in either pigtails or with connectors. It is noted that these measurements are very sensitive to reflections, and that precautions shall be taken to ensure that reflection cavities are not introduced in the test set-up. On the other hand, one of the benefits of measuring GD is to reveal such cavities in the device.

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 uncertainty of 0,02 nm due to temperature.

5.1.6 Detector D1, D2 (optional)

The detectors consist of an optical detector, the associated electronics, and a means of connecting to an optical fibre. The use of 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 minimized with any precautions available. 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 r.f. 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.

5.1.7 RF generator

The r.f. generator delivers an electrical signal that is used for driving the intensity modulator. Also, the signal is delivered to the phase comparator in detectors D1 and D2 as a reference signal. The r.f. generator produces a waveform with a single dominant Fourier component, for example, a sinusoidal, trapezoidal or square wave modulation. Typically, a sinusoidal signal with a frequency in the range of 100 MHz up to 3 GHz is used. The r.f. 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.

5.1.8 Amplitude modulator

The amplitude modulator uses the modulated signal from the r.f. generator to induce the equivalent amplitude modulation on a continuous wave optical signal. The modulator converts the modulated signal from the r.f. generator to a modulated optical signal. The modulator shall have sufficient linearity to produce a good sinusoidal modulation.

5.1.9 Phase comparator

The phase comparator is built in the detector D1 and D2, which compares the phase of the optical signal and the r.f. 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 r.f. signal level shall not affect the phase measurement.

5.1.10 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. Due to the high sensitivity to back reflections, it is necessary to ensure that all of these joints have back-reflection of <-50 dB.

Examples of temporary joints are typically connectors or splices. However, other methods such as vacuum chucks or micromanipulators may be applied. The loss of the TJ shall be stable and shall have a back-reflection at least 20 dB less than the maximum back-reflection to be measured. In the event that connectors are used, it is preferred to use angled ones.

5.1.11 Polarization controller

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° consisting of the 0°, 45° and 90° linear polarization states, and the fourth state on the pole of the Poincaré sphere for circular polarization. If the DUT exhibits polarization mode dispersion, as the polarization controller varies from 0° to 90° linear polarization states, the GD average over all input polarization states can be determined. From a set of GD measurements at all the 4-Mueller-states, the DGD can be calculated. The polarization controller shall be able to provide satisfactory polarization stability over the wavelength range of the measurement.

5.1.12 Reference jumper

The reference jumper is a simple length of optical 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

The measurement setup for this method is shown in Figure 2. A detailed explanation of the various components of this system and their functions is contained below. The setup shown illustrates a transmission measurement of a DUT with two optical ports. The reflectance spectrum of the DUT can also be measured, for instance by using a 2×2 coupler at RB2 and attaching TJ2 to the additional port on the left side of RB2.

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 like temperature, pressure, and mechanical stress. 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.

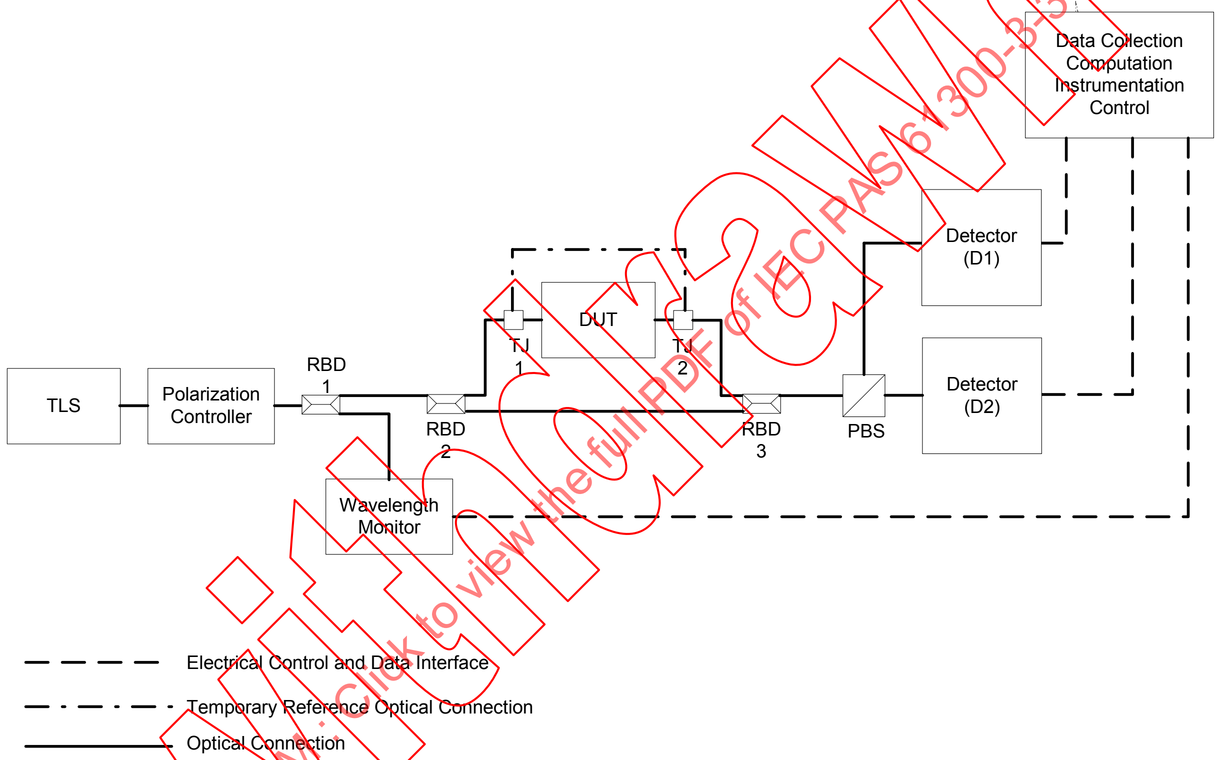

Figure 2 – SWI measurement method apparatus

5.2.1 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 shall 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 10 m, including patch cords, will give an interferogram period of about 20 MHz. Accurate characterization of this requires a substantially smaller resolution. Typically, a high spectral density of measurements is 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.

5.2.2 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.

5.2.3 Reference branching devices (RBD1, 2, 3)

The branching devices, RBD2 and RBD3, are used to establish the interferometer by splitting the optical path so that part of the light passes 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.

5.2.4 Detectors

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 a very short wavelength period, as explained in 5.2.1, so that a high density of measurements versus 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.

5.2.5 Polarization controller

To obtain sufficient interference signal from the interferometer, it shall 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 analyser 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 analyser also permits the calculation of DGD from a set of GD measurements at different polarization conditions.

5.2.6 Polarization analyser

The polarization analyser is the second part of the configuration to assure favourable interference conditions, based on polarization. A practical realization is to use the polarizing beam splitter in combination with the two detectors. When the polarization controller of 5.2.5 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.

6 Measurement procedure

This clause covers the steps required to obtain the GD properties of the DUT with the two apparatus described above

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 $\omega_{opt} = 2\pi\nu_{opt}$ according to

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

In the MPS method, a wavelength tunable source is modulated in amplitude with a sinusoidal waveform at a radio (r.f.)/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 r.f. 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 ν_{opt1}, ν_{opt2}, … ν_{optn}. From the r.f. phase φ_{RF}, the GD is calculated by using the relation,

$$\tau_g(\omega_0) = \left.\frac{\varphi_{RF}}{2\pi f_{RF}}\right|_{\omega_0} = \left.\frac{\varphi_{RF}}{\omega_{RF}}\right|_{\omega_0} = \frac{\Phi_{opt}(\omega_0 + \omega_{RF}) - \Phi_{opt}(\omega_0 - \omega_{RF})}{2\omega_{RF}} = \left.\frac{d\Phi_{opt}(\omega_{opt})}{d\omega_{opt}}\right|_{\omega_0}$$

where $\Phi_{opt}(\omega_0 + \omega_{RF})$ and $\Phi_{opt}(\omega_0 - \omega_{RF})$ represent the optical phases of an upper and lower sideband of the amplitude modulated signal at an optical frequency ω_0, which are separated from the carrier by the modulation frequency ω_{RF}. From measurements of the r.f. 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

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

6.1.2 RF modulation frequency

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

Particular attention should be paid to the wavelength sample spacing and the modulation frequency. In particular, for devices showing high dispersion, the GD difference over the wavelength sampling spacing limits the maximum modulation frequency that can be used without risking phase shifts of more than 360°, which lead to ambiguous results due to phase-wrap errors. The modulation frequency should satisfy

$$f_{RF} < \frac{1}{\Delta\tau},$$

where $\Delta\tau$ 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 the lower side-band of an adjacent acquisition.

Figure 3 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

Modulation frequency GHz	**Wavelength resolution** pm
0,192	3,1
2,112	33,9
4,032	64,6
5,952	95,4
9,792	157,0
11,712	187,8
13,632	218,6
15,552	249,3
17,472	280,1
19,392	310,9
28,992	464,8
38,592	618,7

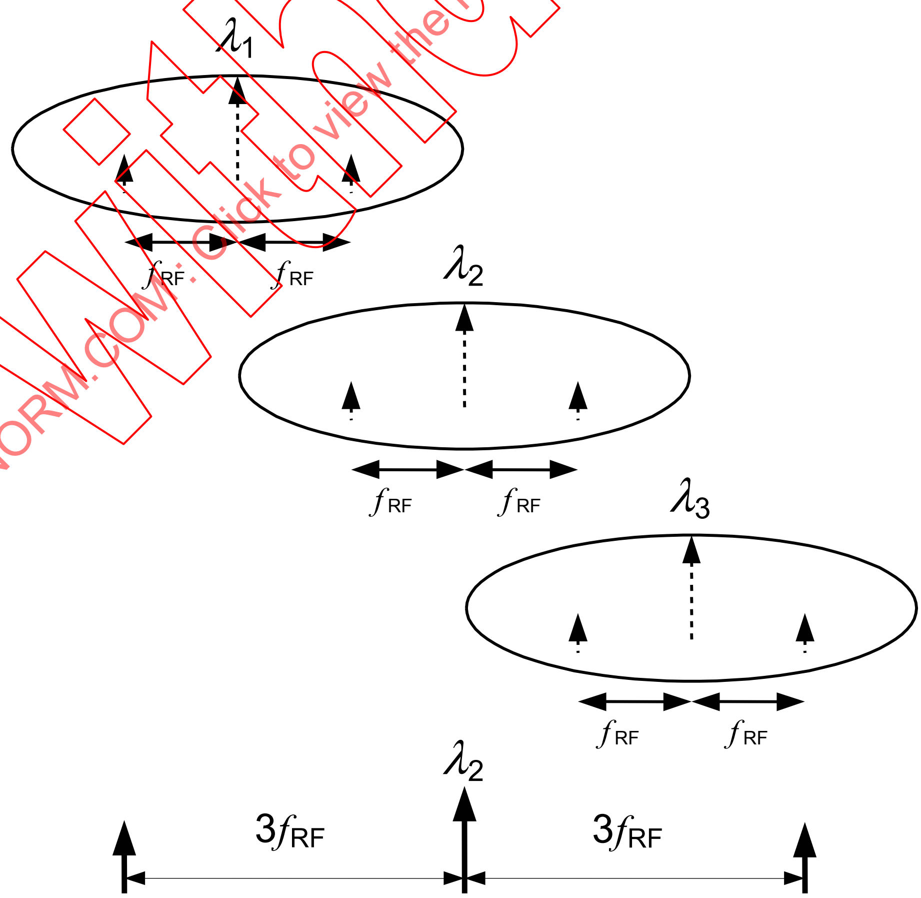

Figure 3 – Sampling at the modulation frequency

6.1.3 Test sequence

Using the setup of Figure 1, the following steps shall be taken.

1. A sinusoidal waveform is generated by an r.f. generator. The frequency f_{RF} is typically selected in a range of 100 MHz to 3 GHz. This sinusoidal waveform will be used to drive the amplitude modulator and to synchronize phase detector D1 and D2. Optionally, the frequency f_{RF} is selected to be the same as the wavelength sample spacing.
2. Optionally, the polarization controller is adjusted to be at 0° linear polarization.
3. With no DUT attached, a fibre patch-cord shall be connected between TJ1 and TJ2. The wavelength of the TLS shall be scanned, 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. The DUT shall be attached at TJ1 and TJ2. The wavelength of the TLS shall be scanned, 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 3-6 can be duplicated with the polarization controller at 90° linear polarization. This allows determination of the GD average over all input states of polarization.

6.1.4 Calculation of 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

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

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

6.1.5 Measurement window

The SW 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 4 for a multiple channel DUT. Each channel is plotted against the corresponding ITU frequency.

Secondly, it may also 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 5. 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.

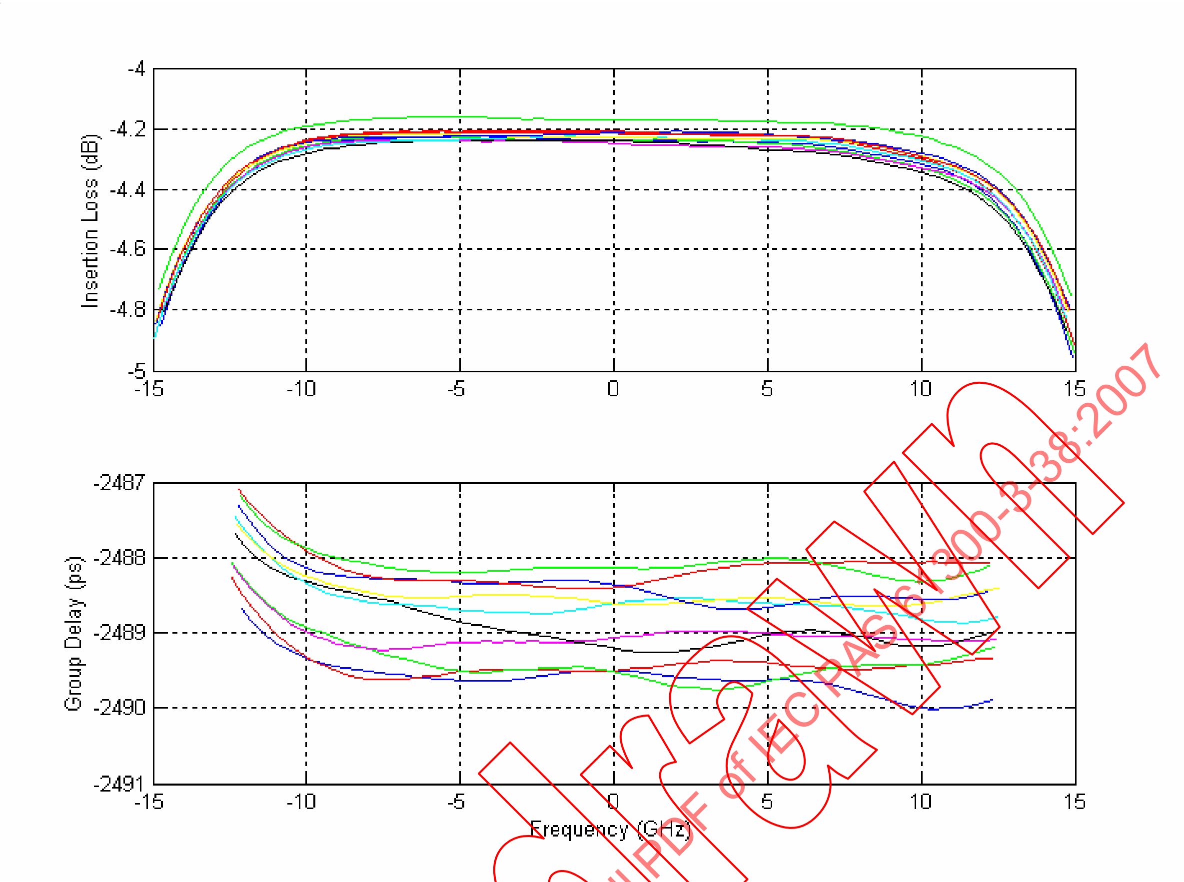

Figure 4 – Measurement window centred on an ITU wavelength with a defined width.

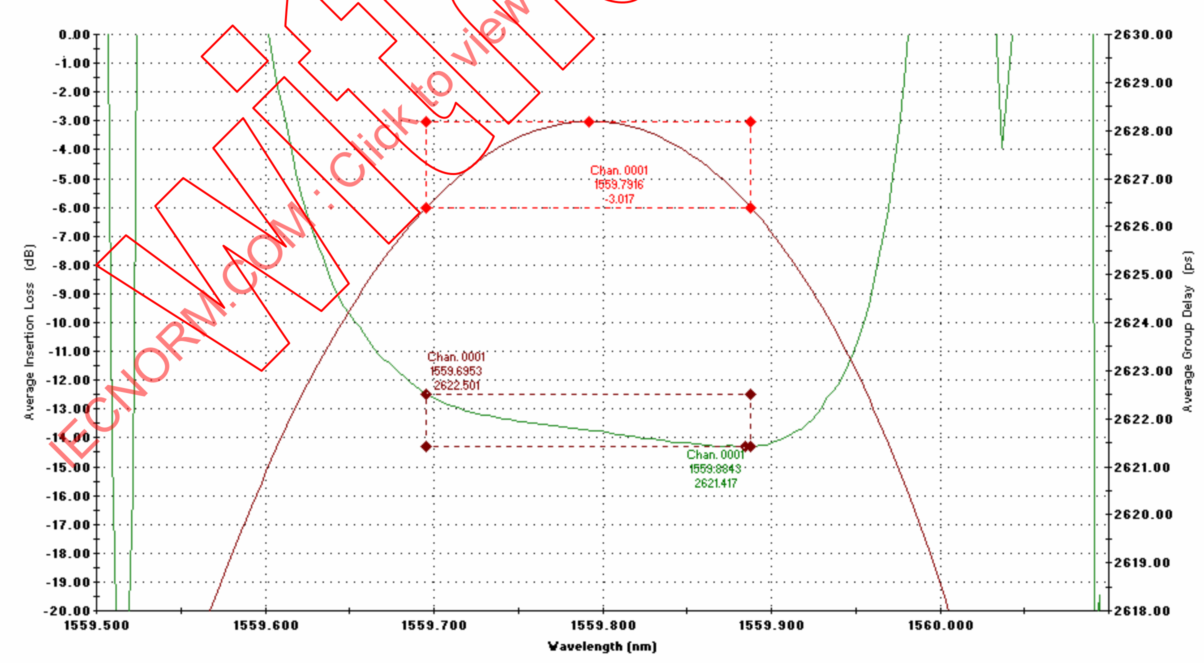

Figure 5 – Measurement window determined by the insertion loss curve at 3dB

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,

$$GD = \frac{d\varphi}{d\omega}.$$

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

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

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 from 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 versus 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, Δλ is given by

$$\Delta\lambda = \lambda^2 / \Delta L,$$

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 versus wavelength, the interferogram, the dependence of the phase on optical frequency can be extracted, which then allows the calculation of the absolute GD. The GD is then also a function of frequency or wavelength.

6.2.2 Test sequence

Using the setup of Figure 2, the following steps shall be taken.

1. With no DUT attached, so that TJ1 and TJ2 are not connected, the polarization controller shall be adjusted 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.

2. The DUT shall be attached at TJ1 and TJ2. The reflectance spectrum of the DUT can also be measured, for instance, by using a 2×2 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. The wavelength of the TLS shall be scanned , recording the wavelengths and signals from D1 and D2, for points with a spacing of 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, 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 2-5 can be duplicated for a second input state of polarization, orthogonal to the first state. This allows determination of the GD averaged over all input states of polarization and of the DGD.

6.2.3 Calculations 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 a non-zero DGD.

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

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

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.

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

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:

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

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

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

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.

$$IL(\omega) = -10\log(T_{ave}(\omega)).$$

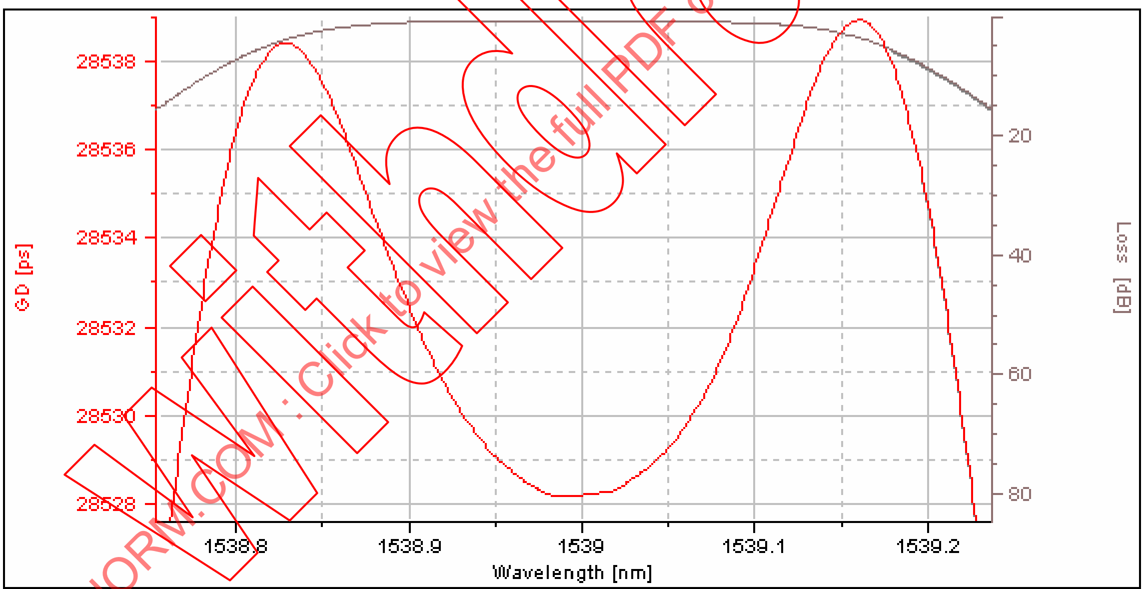

Figure 6 – GD and loss spectra for a 50 GHz-channel-spacing DWDM filter

Sample results for the GD and IL spectra of a 50 GHz band pass filter are shown in Figure 6.

7 Analysis

Having acquired the GD data, there are several derived or alternate parameters that can be used. The following subclauses deal with methods for extracting this information.

7.1 Noise reduction of group delay measurement

Various methods are used to reduce the noise on the measurement traces.

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. In the case where DWDM components are characterized, typical widths of such windows are 5 pm to 10 pm. Broadband components may allow window widths of up to 1 nm and more. It shall be taken into account that the optical signal is spectrally broadened due to the r.f. modulation and therefore already provides a spectrally averaged measurement value. For these reasons it is required to state the applied r.f. 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

$$\varphi(\nu_{opt}) = \varphi(\nu_{opt0}) + 2\pi\tau_g(\nu_{opt} - \nu_{opt0})$$

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

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

$$CD(\lambda_0) = \left.\frac{\mathrm{d}\tau_g(\lambda_0)}{\mathrm{d}\lambda_0}\right|_{\lambda_0}$$

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

$$CD(\lambda_i) = \frac{\tau_g(\lambda_{i+1}) - \tau_g(\lambda_{i-1})}{\lambda_{i+1} - \lambda_{i-1}}$$

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, a GD noise will be amplified in the CD calculation. There are many ways to minimize the calculated CD noise. Normally, two methods are recommended.

7.3.1 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 narrowband devices. The number of measurement points filtered (or averaged) over a spectral window depends on the CD noise improvement, not averaging out relevant details of the measurement and not distorting the processed GD curve.

7.3.2 Curve fit

A curve shall be fitted, by least mean squares procedure, to GD data over a measurement window defined in 6.1.5. The 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 the least mean squares procedure, to GD 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 ±0,5ps of the raw data.
3. The CD is calculated from the differentiation of the fitted GD curve with respect to wavelength. The wavelength step used for calculation is 6 pm.

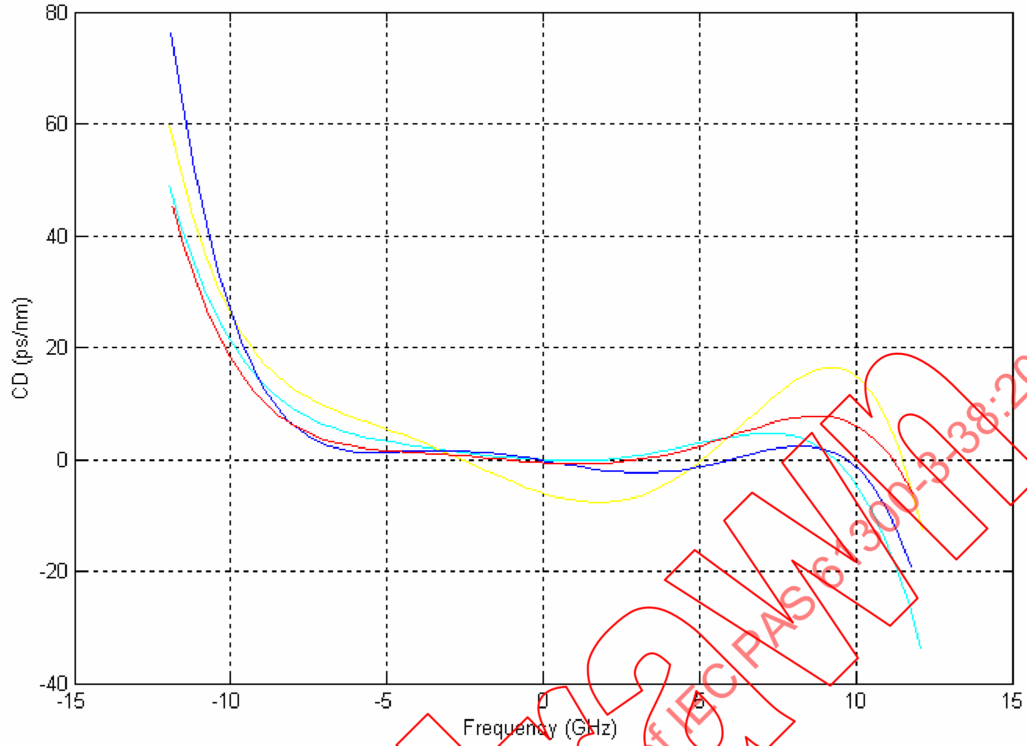

Figure 7 – Calculation of CD from the differentiation of the fitted GD curve with respect to wavelength

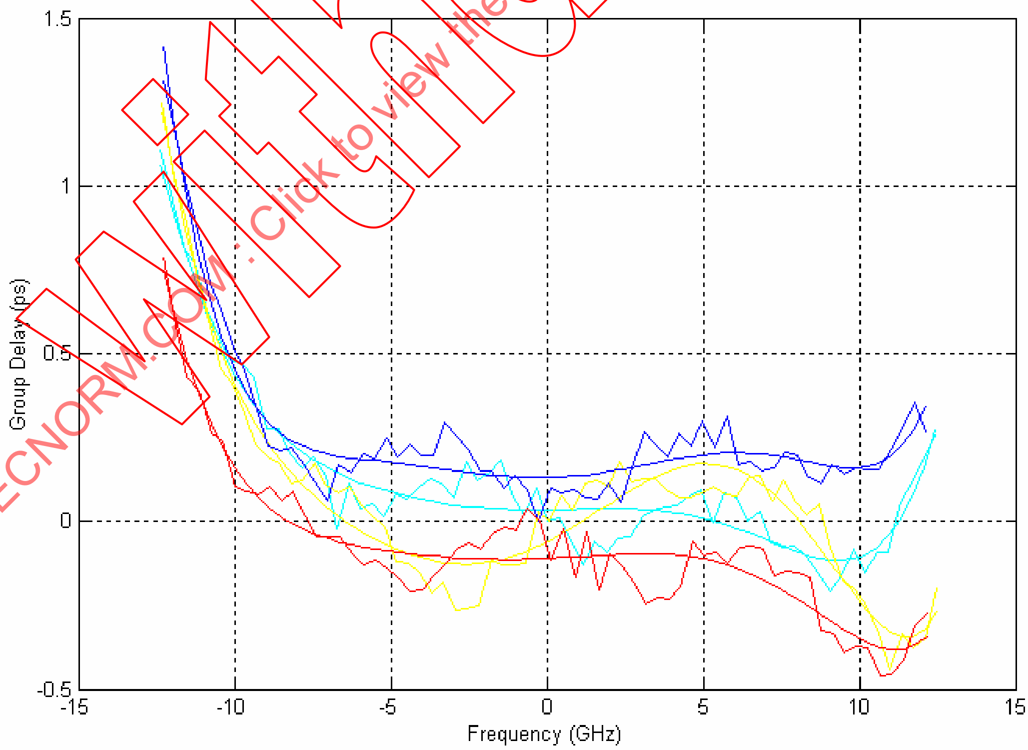

Figure 8 – Fitting of 6th order polynomial curve by least mean squares procedure to GD data over a 25GHz optical BW centred on the ITU frequency