

Fibre optic communication subsystem test procedures —

Part 4-4: Cable plants and links — Polarization mode dispersion measurement for installed links

The European Standard EN 61280-4-4:2006 has the status of a British Standard

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National foreword

This British Standard is the official English language version of EN 61280-4-4:2006. It is identical with IEC 61280-4-4:2006.

The UK participation in its preparation was entrusted by Technical Committee GEL/86, Fibre optics, to Subcommittee GEL/86/3, Fibre optic systems and active devices, which has the responsibility to:

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- present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep UK interests informed;
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**Fibre optic communication subsystem test procedures
Part 4-4: Cable plants and links -
Polarization mode dispersion measurement for installed links
(IEC 61280-4-4:2006)**

Procédures d'essai des sous-systèmes
de télécommunication à fibres optiques
Partie 4-4: Installation de câbles et liens -
Mesure de la dispersion de mode
polarisation pour les liaisons installées
(CEI 61280-4-4:2006)

Prüfverfahren für Lichtwellenleiter-
Kommunikationsundersysteme
Teil 4-4: Kabelnetze
und Übertragungsstrecken -
Messung der
Polarisationsmodendispersion
von installierten Übertragungsstrecken
(IEC 61280-4-4:2006)

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Comité Européen de Normalisation Electrotechnique
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Foreword

The text of document 86C/683/FDIS, future edition 1 of IEC 61280-4-4, prepared by SC 86C, Fibre optic systems and active devices, of IEC TC 86, Fibre optics, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 61280-4-4 on 2006-02-01.

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Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 61280-4-4:2006 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 60793-1-48	NOTE	Harmonized as EN 60793-1-48:2003 (not modified).
IEC 61290-11-1	NOTE	Harmonized as EN 61290-11-1:2003 (not modified).
IEC 61290-11-2	NOTE	Harmonized as EN 61290-11-2:2005 (not modified).

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FIBRE OPTIC COMMUNICATION SUBSYSTEM TEST PROCEDURES –

Part 4-4: Cable plants and links – Polarization mode dispersion measurement for installed links

1 Scope

This part of IEC 61280 provides uniform methods of measuring polarization mode dispersion (PMD) of single-mode installed links. An installed link is the optical path between transmitter and receiver, or a portion of that optical path. These measurements may be used to assess the suitability of a given link for high bit rate applications or to provide insight on the relationships of various related transmission attributes. The principles of this document are aligned with those of the optical fibre and optical fibre cable test method, IEC 60793-1-48 (see Bibliography), which focuses on aspects related to the measurement of factory lengths. Instead, this document focuses on the measurement methods and requirements for measuring long lengths that might be installed – and that might also include other optical elements, such as amplifiers, DWDM components, multiplexers, etc.

PMD is a statistical parameter. The reproducibility of measurements depends on the particular method, but is limited also by the PMD level of the link. Gisin [3]⁵⁾ derived a theoretical limit to this reproducibility, by assuming an infinite range of measured wavelengths and ideal measurement conditions.

NOTE 1 Test methods for factory lengths of optical fibres and optical fibre cables are given in IEC 60793-1-48.

NOTE 2 Test methods for optical amplifiers are given in IEC 61290-11-1 and IEC 61290-11-2.

NOTE 3 Test methods for passive optical components are given in IEC 61300-3-32.

NOTE 4 Guidelines for the calculation of PMD for links that include components such as dispersion compensators or optical amplifiers are given in IEC 61282-3.

With the exception of Method D, all methods in this document may be used to measure the PMD in the gain band of links that include pumped optical amplifiers. For these links, amplified spontaneous emission (ASE) noise can generate depolarized spectral energy in the neighbourhood of the measurement wavelength. This will, in general, reduce the accuracy of the measurement. For Methods A, B, C, E and F, this effect can be moderated by implementing an optical or electrical filter at the receive end. However, optical filtering will not remove the ASE right under the signal spectrum. The accuracy will then be limited by a lower degree of polarization (DOP), if the spectral width of the filter cannot be sufficiently reduced as with a broadband source. Lower DOP may require the signal to be integrated longer to be meaningful or the result will become too noisy and interpretation will be erroneous.

None of the methods is suitable for measuring the PMD of links with polarization dependent loss (PDL) in excess of 10 dB. Links with PDL values less than 1 dB can be measured with reasonable accuracy. Measurement accuracy may be compromised by the presence of PDL in excess of 1 dB.

⁵⁾ Figures in square brackets refer to the bibliography.

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 60793-1-44: *Optical fibres – Part 1-44: Measurement methods and test procedures – Cut-off wavelength*

3 Symbols and abbreviated terms

c	Velocity of light in vacuum (299792458 m/s)
h	Coupling length
L	Length of the link
t_c	Optical source coherence time (Method C)
$\delta\lambda$	Wavelength increment (step size)
$\delta\nu$	Optical frequency increment (step size)
$\Delta\lambda$	Optical source spectral width or linewidth (FWHM unless noted otherwise)
$\Delta\theta$	Rotation angle on Poincaré sphere
$\delta\tau$	Differential arrival times of different polarization components.
$\delta\tau_{\min}$	Minimum $\delta\tau$ value that can be measured
$\Delta\tau$	Differential group delay value
$\langle\Delta\tau\rangle$	Average DGD over a wavelength range or PMD_{average} value
$\langle\Delta\tau^2\rangle^{1/2}$	RMS DGD over a wavelength range or PMD_{RMS} value
$\Delta\tau_{\max}$	Maximum $\delta\tau$ value that can be measured
$\Delta\omega$	Angular frequency variation in Method B
λ	Test wavelength used to measure PMD
λ_0	Central wavelength of the light source
ν	Optical light frequency
σ_R	Second moment of Fourier transform data
σ_0	RMS width of the squared autocorrelation envelope
σ_x	RMS width of the squared cross-correlation envelope
σ_ε	RMS width of interferogram
ω	Angular optical frequency
ASE	Amplified spontaneous emission
DGD	Differential group delay
DOP	Degree of polarization
DUT	Device under test
FA	Fixed analyzer

FET	Field effect transistor
FWHM	Full-width half-maximum
GINTY	General interferometric analysis
I/O	Input-output
JME	Jones matrix eigenanalysis
LED	Light emitting diode
MPS	Modulation phase shift
PDL	Polarization dependent loss
PIN (diode)	Positive insulated negative
PMD	Polarization mode dispersion
PPS	Polarization phase shift
PSA	Poincaré sphere analysis
PSP	Principal SOP
RBW	Resolution bandwidth
RMS	Root mean-square
SOP	State of polarization
SPE	Stokes parameter evaluation
TINTY	Traditional interferometric analysis

4 Background on PMD properties

PMD causes an optical pulse to spread in the time domain. This dispersion could impair the performance of a telecommunications system. The effect can be related to differential phase and group velocities and corresponding arrival times, $\delta\tau$, of different polarization components of the signal. For a sufficiently narrowband source, the effect can be related to a differential group delay (DGD), $\Delta\tau$, between pairs of orthogonally polarized principal states of polarization (PSP) at a given wavelength. For broadband transmission, the delays bifurcate and result in an output pulse that is spread out in the time domain. In this case, the spreading can be related to the root-mean square (RMS) of DGD values.

In long fibre spans, DGD varies randomly both in time and wavelength since it depends on the details of the birefringence along the entire fibre length. It is also sensitive to time-dependent temperature and mechanical perturbations on the fibre. For this reason, a useful way to characterize PMD in long fibres is in terms of the expected value, $\langle\Delta\tau\rangle$, or the mean DGD over wavelength. In principle, the expected value $\langle\Delta\tau\rangle$ does not undergo large changes for a given fibre from day to day or from source to source, unlike the parameters $\delta\tau$ or $\Delta\tau$. In addition, $\langle\Delta\tau\rangle$ is a useful predictor of transmission performance.

The term "PMD" is used both in the general sense of two polarization modes having different group velocities (one having the fastest velocity and corresponding earliest arrival time and the other the slowest velocity and corresponding latest arrival time, the difference between the two arrival times being the DGD), and in the specific sense of the expected value $\langle\Delta\tau\rangle$. The latter gives us the strict definition of PMD for the purposes of this document. The DGD $\Delta\tau$ or pulse broadening $\delta\tau$ can be averaged over wavelength, yielding $\langle\Delta\tau\rangle_\lambda$, or frequency,

yielding $\langle \Delta\tau \rangle_v$, or time, yielding $\langle \Delta\tau \rangle_t$, or temperature, yielding $\langle \Delta\tau \rangle_T$. For most purposes, it is not necessary to distinguish between these various options for obtaining $\langle \Delta\tau \rangle$.

$$PMD_{AVG} = \langle \Delta\tau \rangle \quad (1a)$$

The expression in Equation (1a) is sometimes called the linear average of the DGD values. It is reported for the purposes of specifying optical fibre cables and many other components. Another metric, the RMS of the DGD values is also reported by some measurement instruments, particularly those based on Method C. It is defined as:

$$PMD_{RMS} = \langle \Delta\tau^2 \rangle^{1/2} \quad (1b)$$

For many links, the DGD values are randomly distributed closely as a Maxwell distribution. Under the assumption of a perfect fit with a Maxwell distribution, the linkage between the two metrics, linear average DGD and RMS DGD is given by Equation (1c).

$$\langle \Delta\tau \rangle = \left(\frac{8}{3\pi} \right)^{1/2} \langle \Delta\tau^2 \rangle^{1/2} \quad (1c)$$

NOTE 1 Equation (1c) applies if the distribution of DGD values is Maxwellian. This assumption may not be valid if there are highly birefringent elements (relative to the rest of the link) in the optical path. A multiplier of from 3 to 3,7 (see IEC 61282-3), depending on probability limits accepted by the link owner, is applied to the PMD_{AVG} value to determine the maximum DGD, which is specified for ITU-T compliant links. This multiplier is based on a Maxwell assumption and reflects a very long tail of that distribution. If the link includes a highly birefringent element, both the PMD_{AVG} and PMD_{RMS} metrics will increase relative to the actual tail of the DGD distribution (implying that a reduced multiplier could be used), but Equation (1c) may not be maintained because the DGD distribution will begin to resemble one based on the square root of a non-central chi-square distribution with three degrees of freedom. In these cases, the PMD_{RMS} value will generally be larger relative to the PMD_{AVG} value indicated by Equation (1c). This condition is indicated by “flat tops” on the fringe envelopes from the time domain measurement methods such as Method C and by bimodal DGD distributions from the frequency domain measurement methods such as Method B.

The expected value operator in the above equations refers to the long term expected value across all wavelengths. In practice, a finite wavelength range at a particular point of time and condition are sampled and some form of mean of the data is calculated. The expected value of these calculated means is equal to the long-term expected values, assuming ergodicity over time, wavelength, and condition. If this assumption is not valid, the result will vary depending on the particular wavelengths that are sampled. For ergodic conditions, the reproducibility of the measurement will vary with wavelength range and PMD level [3]⁶⁾.

NOTE 2 Ergodic: of or relating to a process in which every sequence or sizable sample is equally representative of the whole.

5 Measurement methods

5.1 Methods of measuring PMD

Six basic methods of measuring PMD are given. Details specific to each are given in normative annexes. The methods are listed below in order of their introduction. For some methods, multiple approaches of analyzing the measured results are also provided.

⁶⁾ Figures in square brackets refer to the bibliography.

- Method A Fixed analyzer (FA)
 - Fourier transform (FT)
- Method B Stokes parameter evaluation (SPE)
 - Jones matrix eigenanalysis (JME)
 - Poincaré sphere analysis (PSA)
- Method C Interferometry (INTY)
 - Traditional analysis (TINTY)
 - General analysis (GINTY)
- Method D Stokes parameter evaluation using back-reflected light
 - Jones matrix eigenanalysis (JME)
 - Poincaré sphere analysis (PSA)
- Method E Modulated phase-shift
 - Full search
 - Mueller set analysis
- Method F Polarization phase shift (PPS)

Each method has advantages in certain respects and disadvantages in others. For example:

Methods A, B, D, E and F may rely on measurements that can be disrupted if the link is vibrating such as in the case of aerial cables if the optical properties of the fibre change within the time used to measure the data for calculating individual DGD values. Fast measurement rates have been implemented in some commercial field test systems to reduce this effect. Method C can be used in this case because it uses a broadband source and interferometry to deduce the PMD from the time-domain cross-correlation envelope of the measured interferogram.

Methods B, E and F require a communication and coordination between the sources and receive ends during a measurement, requiring an additional communication channel when the link ends are not co-located. The link itself may also be used for this channel. Using Method D, all measurement equipment is co-located whether or not the links ends are co-located, but special care shall be taken in the fibre end preparation at both ends. Using Method A and C, the source and receive equipment may have to be separated, but there is no need for active coordination of the source and receive equipment during the course of a measurement.

Method E can yield DGD results for the narrowest occupied optical bandwidth of all the methods, but requires the DGD of the link to be in excess of around 0,5 ps. The bandwidth requirement of Methods B, D and F is larger than that of Method E because numerical differentiation of the output data collected at two closely separated wavelengths is required, but these methods can measure DGD at the lowest of levels. Method C does not provide measurements of individual DGD values, but does provide the RMS DGD (PMD_{RMS}) over the wavelengths of the source spectrum.

Method F is similar to Method E, when Method E is implemented with the Mueller matrix approach. Method F, however, requires measurements at two adjacent wavelengths to obtain one DGD value, similar to Methods B and D.

All methods require light sources that are controlled at one or more known and distinct states of polarization (SOP). All methods require injecting light across a spectral region to obtain a PMD value that is characteristic of that region (for example, 1 300 nm or 1 550 nm).

The methods differ in:

- the spectral characteristics of the source;
- the bandwidth characteristics of the detection system;
- the physical characteristics that are actually measured;
- the analysis methods.

Method A requires only one input SOP and uses a fixed analyzer to track the relative change in power of one element of the Stokes vectors. When a Fourier transform is applied to this data, the result is a virtual half-interferogram, which is evaluated in a manner similar to Method C (TINTY).

Method B measures PMD_{AVG} by measuring a polarimetric response to a change of narrowband light across a wavelength range. For each wavelength, three known and distinct SOPs such as for example linear SOPs at nominally 0°, 45° and 90° (orthogonal on the Poincaré sphere) shall be launched and the output Stokes vector that is transmitted through the link is measured.

The change of these Stokes vectors with angular optical frequency (wavelength), ω , and, with change in input SOP, yields the DGD as a function of wavelength through relationships that are based on the following definitions:

$$\frac{d\hat{s}(\omega)}{d\omega} = \hat{\Omega}(\omega) \times \hat{s}(\omega) \quad (2)$$

$$\Delta\tau(\omega) = \left| \hat{\Omega}(\omega) \right| \quad (3)$$

where

$\hat{s}$ is the output Stokes vector at angular optical frequency ω

$\hat{\Omega}$ is the PSP vector, also called polarization dispersion vector (PDV) at angular optical frequency ω

$\Delta\tau$ is the DGD at angular optical frequency ω .

The JME is completed by transforming the output Stokes vectors to Jones matrices [2], appropriate combination of the matrices at adjacent wavelengths, and calculation of the eigenvalues of the result followed by the application of an argument formula to obtain the DGD at the base frequency.

The PSA is completed by doing matrix algebra on the normalized output Stokes vectors, to infer the output Stokes vector associated with circular birefringence at adjacent wavelengths, followed by the application of an arcsine formula to obtain the DGD at the base frequency.

For both JME and PSA, the average of the DGD values for a given wavelength range yields the PMD value for that range. The JME and PSA are mathematically equivalent. When using a narrowband source the usual care should be taken to minimize optical reflections that could give rise to coherent interference effects.

In addition, in the case of a start-stop-measure system (by opposition to a swept system), the step size of the narrowband source shall be carefully selected in accordance with the expected DGD spectrum (DGD variation as a function of wavelength). More detail on step-size selection is given in B.2. The linewidth of the narrowband source shall then be adjusted to the selected step size in accordance with the Nyquist criterion.

Method C is based on a broadband light source that is polarized at one or more known and distinct SOPs. The cross-correlation of the emerging electromagnetic field is determined by the interference pattern of the output light. The characterization of this pattern is done by computing the RMS width of the cross-correlation envelope of the interferogram for TINTY or the squared RMS widths of both the cross-correlation and autocorrelation envelopes of the interferogram for GINTY. These RMS widths yield the PMD value for the wavelength range associated with the source spectrum (the source bandwidth). The accuracy of Method C (TINTY) may be reduced for links containing amplifiers, which may limit the source spectrum. This is not the case for GINTY. Furthermore, TINTY is applicable upon a set of stringent requirements that GINTY is not subjected to. Method C measures the PMD_{RMS} value only.

Method D is in principle the same as Method B, but the output Stokes vectors that are reflected from the end of the link back to the source are measured to obtain DGD values. A modified formula that takes the reflection into account is used to calculate the PMD value for a given band. Since the reflection is required, the method is not suitable for links containing isolators (often found in optical amplifiers). Care should also be taken as in all other cases where a narrowband light source is used in order to avoid coherence interference effects and Fabry-Perot etalon effects that could show as false DGD. These effects produce delays that will be recorded in any case. Results reported from literature have demonstrated that Method D is limited to distances of the order of 40 km, except if a reflector is used at the end of the plant to enhance the reflected light intensity.

Method E measures the phase difference between two or more input SOPs for a modulated narrowband light source. The full search technique requires launching an alternating pair of orthogonal input SOPs to obtain a given phase shift. The axis of this pair is varied across the entire Poincaré sphere to obtain the maximum phase shift. The maximum phase shift difference that is found is used to deduce the DGD at the centre wavelength of the source spectrum. The Mueller set technique [1] requires launching four SOPs per wavelength (source spectrum), representing a Mueller set. Analysis of the phase shifts associated with these SOPs yields a DGD value for the wavelength. When the measurement is conducted for a number of wavelengths in a wavelength range, the average of the DGD values yields the PMD value for that range.

Method F measures the phase differences between different known and distinct SOPs such as linear and orthogonal input SOPs – similar to Method E. It is different from Method E in that only two orthogonal input SOPs are required. However, because of this, results at two wavelengths are required to calculate one DGD value.

Information common to all six methods is contained in Clauses 1 through 8, and requirements pertaining to each individual method appear in Annexes A, B, C, D, E and F, respectively.

5.2 Reference test method

There is no reference test method because each method has its own particular optimal applications.

6 Apparatus

The following apparatus is common to all measurement methods. Annexes A, B, C, D, E and F include layout drawings and other equipment requirements for each of the six methods, respectively.

All the transmission elements of the apparatus can contribute to the measured PMD. It is essential that these elements be selected for their lowest maximum DGD and PDL in the same spectral range of the PMD measurement. It may be necessary to assess the overall contribution of these elements by performing a measurement on a short length (2 m) of low PMD fibre. When the PMD contribution of these elements is significant, one option is to subtract, in quadrature, the measurement system PMD value from the measured link PMD value before reporting a final value.

6.1 Light source and polarizers

See Annexes A, B, C, D, E and F for detailed options of the spectral characteristics of the light source. The source shall produce sufficient radiation at the intended wavelength(s) and be stable in intensity over a time period sufficient to perform the measurement and should cover the required range of wavelengths for PMD determination for the band of interest.

For all methods, the light source is required to be polarized at one or more known and distinct SOPs before it is injected into the fibre under test. Polarizers, polarization adjusters using waveplates, liquid crystal retardation plates, loops of birefringent fibre that are mechanically moved, or electro-optic crystal devices may be used to set the source SOP at the input of the fibre under test as well as the analyzer polarization axis at the output of the fibre under test. The performance of the polarization adjuster setup can be verified by measuring the output power at three linear known and distinct SOPs. If the output powers are within 3 dB of one another, the adjuster setup is suitable.

For Methods A, B, D (when implemented using a narrowband tuneable light source – TLS), E and F, the effective spectral width (Gaussian spectrum, full-width half-maximum – FWHM) of the source, $\Delta\lambda$, shall be narrow enough so that light emerging from the fibre remains polarized under all conditions of measurement and for all DGD values being measured. A DOP of 90 %

or greater is preferred, although measurements may be performed with values as low as 25 % with reduced precision. The relationship between DOP, the spectral width, $\Delta\lambda$, wavelength centre, λ_0 , and DGD, $\Delta\tau$, is given by:

$$DOP(\%) = 100 \exp \left[-\frac{1}{4 \ln(2)} \left(\frac{\pi c \Delta \tau \Delta \lambda}{\lambda_0^2} \right)^2 \right] \quad (4)$$

6.2 Input optics

A connectorized fibre pigtail may be employed to launch the light into the link. The rest of the input optics precedes this pigtail. The connection shall be stable over the course of the measurement.

For Method D, there are special requirements on interface of measurement system pigtail and the link to control reflections (see Annex D).

6.3 Cladding mode stripper

Use a device that extracts cladding modes from the link fibre. Under some circumstances the fibre coating will perform this function.

6.4 High-order mode filter

Use a means to remove high-order propagating modes in the desired wavelength range that is greater than or equal to the cut-off wavelength of the link (see IEC 60793-1-44). For example, a one-turn bend of radius = 30 mm on the fibre is generally sufficient.

6.5 Output positioner

A connectorized fibre pigtail may be employed to transmit the link to the output optics. This connection shall be stable over the course of the measurement.

For Method D, the light reflected from the far end of the link (relative to the light source) may require a special end preparation to maximize the reflection. For this method, the output of the connection is the same as the input connection.

6.6 Output optics

See the appropriate annex (A, B, C, D, E or F).

Some link measurements may require the use of the combination of an optical amplifier and variable attenuator in the test set-up to maintain power at a level that is suitable for the analyzer detector. In this case, such power adjustment apparatus is generally placed immediately before the detector.

For Method D, the output optics are co-located with the input optics.

6.7 Detector

For signal detection, an optical detector is used which is linear and stable over the range of intensities, wavelengths and measurement times that are encountered in performing the measurement. A typical system might include synchronous detection by a chopper/lock-in amplifier, an optical power meter, optical spectrum analyzer, interferometer, or a polarimeter. To use the entire spectral range of the source, the detection system shall have a wavelength range, which includes the wavelengths produced, by the light source. See the appropriate annex (A, B, C, D, E or F) for additional details.

6.8 Computer

Use a computer to perform operations such as controlling the apparatus, taking intensity measurements, and processing the data to obtain the final results.

6.9 Means to reduce the effects of amplified spontaneous emission

ASE results in the depolarization of the received light. Depending on the implementation and method, the following alternatives may be used.

- Modulation of the signal light in combination with an electrical filter within the detection electronics.
- A tuneable optical filter locked to the wavelength of the signal, placed at the output of the fibre link.

7 Sampling and specimens

A specimen is a length of single-mode optical fibre link. Except for Method C, the link should be measured at a time when vibrations or temperature variations are minimized over the time period of the measurement. If the link includes optical amplifiers, they should be turned on.

8 Procedure

- a) Prepare the ends of the link by attaching the required connector.

NOTE For Method D, an angled fibre end is required at the input to minimize reflections from the input end.

- b) Attach the ends to the input and output optics.

NOTE For Method D, the input and output optics are the same; the end of the link to which they are attached will be called the input end. The output end of the link may need special preparations to ensure an adequate reflection back to the input end.

- c) Engage the computer to complete the scans and measurements found in Annexes A, B, C, D, E or F for the four measurement methods.
- d) Complete documentation

9 Calculation or interpretation of results

Annexes A, B, C, D, E and F provide calculations to convert the measured data into DGD or PMD values.

IEC 61282-3 provides information on the calculation of the link PMD based on the statistics of optical fibre and component values.

10 Documentation

10.1 Information required for each measurement

- Link
 - Identification
 - Description, for example presence of optical amplifiers or other components
 - Length (km)
 - Fibre and cable types
- Testing date
- Test results
 - PMD value as PMD_{AVG} or PMD_{RMS}
 - Spectrum and linewidth of the test set-up light source
 - DGD as a function of wavelengths or/and frequencies for Methods B, D, E, F
 - Interferogram for Method C
 - Intensity as a function of wavelengths or frequencies and Fourier transform for Method A
- Wavelength or frequency range over which the measurement is performed

10.2 Information to be available

The following information will normally be traceable by recording the make, model, serial number, and relevant module details of the equipment used.

- Test set-up
 - Measurement method
 - Calculation approach (analysis)
 - Description of equipment
 - Source detailed characteristics
 - Analyzer detailed characteristics
 - Any other accessories if used
 - Calibration
 - Date of latest calibration
 - Method of calibration
 - Uncertainty analysis
- For Methods B, D and E, the number of wavelengths sampled
- For Method C, the type of fringe detection technique

11 Specification information

- Wavelength range
- Any deviations from this procedure

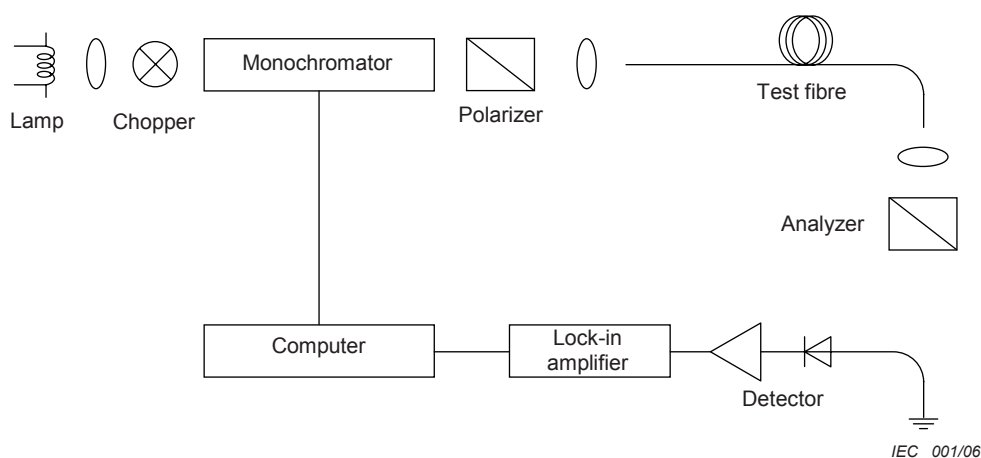
Annex A (normative)

Fixed analyzer method

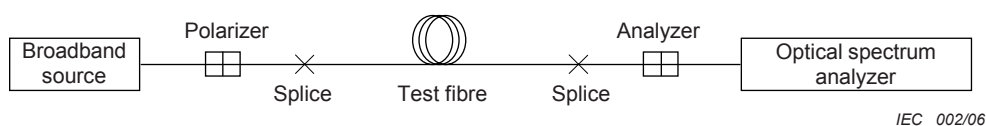
This annex contains requirements specific to Method A, fixed analyzer (FA) measurement method.

A.1 Apparatus

Figure A.1 shows possible block diagrams.



(a) Set-up using a narrowband source based on lamp and monochromator



(b) Set-up using a broadband source

Figure A.1 – Block diagrams for fixed analyzer

A.1.1 Light source

In all cases, two kinds of light sources may be used, depending on the type of analyzer. A narrowband source such as the broadband lamp and monochromator combination shown Figure A.1(a) can be used with a polarization analyzer. A broadband source shown in Figure A.1(b) can be used with a narrow bandpass filtering analyzer such as an optical spectrum analyzer or an interferometer used as a Fourier transform spectrum analyzer placed before the analyzer. In the case of broadband source, the width of the filter is taken as the spectral width for the purpose of calculations.

In both cases, the spectral width shall be sufficiently small to maintain the desired DOP (see 5.1), but not too small compared to the selected step size to avoid unnecessary coherent interference effects and other spurious noises. In both cases, the range of wavelengths shall be sufficient to provide a PMD measurement of sufficient precision at the specified wavelength region (see A.3).

To insure that all features in the optical spectrum are adequately resolved, the spectral width should satisfy

$$\Delta\lambda / \lambda_0 < (8\nu\Delta\tau_{\max})^{-1} \quad (\text{A.1})$$

where

$\nu = c/\lambda$ is the optical frequency,

$\Delta\lambda$ is the spectral width, and

$\Delta\tau_{\max}$ is the maximum anticipated DGD.

For λ in the vicinity of 1 550 nm, Equation (A.1) reduces to the condition that $\Delta\lambda$ (nm) should be less than the reciprocal of $\Delta\tau$ (ps).

A.1.2 Analyzer

The angular orientation of the analyzer is not critical, but should remain fixed throughout the measurement. With negligible mode coupling or low PMD values, some adjustment of the analyzer may be helpful in maximizing the amplitude of the oscillations in Figure A.2 – which can also be achieved by rotating the fibre at splices or connectors.

NOTE The analyzer can be replaced by a polarimeter.

A.2 Procedure

A.2.1 Wavelength range and increment

The procedure requires measuring the power as a function of wavelengths (or optical frequencies) over a range at a defined wavelength increment once with the analyzer in the optical path and once without. The wavelength range can influence the precision of the result (see A.3). The wavelength increment should be selected to satisfy Equation (A.1), with the wavelength increment replacing $\Delta\lambda$.

If the Fourier transform method is used, the wavelength increment should ideally be uniform in optical frequency and the number of steps should be a power of 2. The monochromator step-size, expressed in optical frequency, $\delta\nu$, shall be a factor of two smaller than the “oscillation frequency” corresponding to the maximum DGD measured. Because of the large amount of power outside the second moment for highly mode-coupled fibres, the Nyquist condition requires a frequency increment smaller than three times the frequency of the RMS width (second moment) associated with the maximum anticipated DGD. That is:

$$\frac{1}{6\delta\nu} > \Delta\tau_{\max} \quad (\text{A.2})$$

NOTE 1 If from the Fourier transform, it is evident that there is significant energy near $\Delta\tau_{\max}$, the measurement should be repeated with a reduced increment.

NOTE 2 The source spectral width is generally equal to or less than the smallest wavelength increment. For example, for $\Delta\tau_{\max} = 0,67$ ps, a monochromator spectral width of 2 nm at 1 550 nm ($\delta\nu = 249$ GHz) is typical.

A.2.2 Complete the scans

Complete the scan with the analyzer in the light path. Record the received power as $P_A(\lambda)$.

Remove the analyzer from the light path and repeat the scan. Record the total received power as $P_{\text{Tot}}(\lambda)$.

Calculate the power ratio, $R(\lambda)$ as follows.

$$R(\lambda) = \frac{P_A(\lambda)}{P_{\text{Tot}}(\lambda)} \quad (\text{A.3})$$

Figure A.2 shows an example of a randomly mode-coupled result typical of a link application.

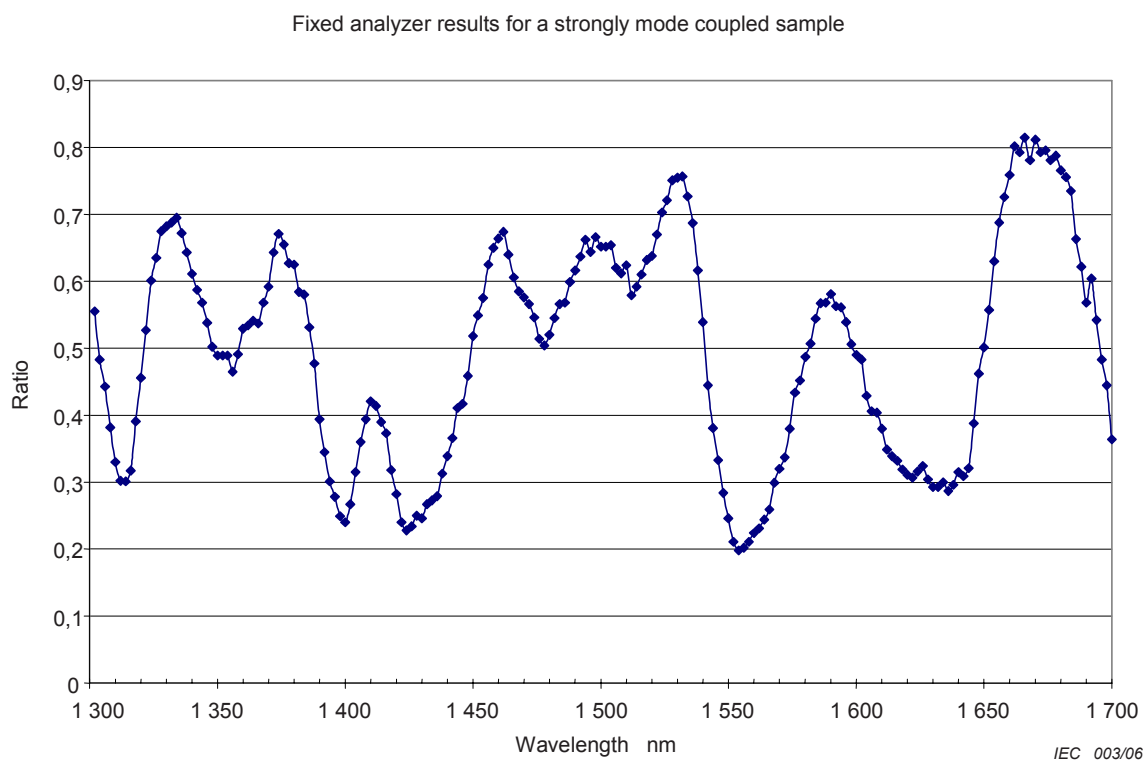


Figure A.2 – Example of the R-function for the fixed analyzer method

An alternative procedure is to leave the analyzer in place on the second scan, but rotate it 90° . Record the power as $P_B(\lambda)$. The formula for the power ratio is then:

$$R(\lambda) = \frac{P_A(\lambda)}{P_A(\lambda) + P_B(\lambda)} \quad (\text{A.4})$$

NOTE 1 The cosine Fourier transform of the difference, $P_B - P_A$, divided by the sum, is the cross-correlation function.

NOTE 2 If a polarimeter is used as the detection element, the normalized Stokes parameters are measured versus wavelength. The three spectral functions (one per vector element) are independent of received power and correspond to three independent difference functions between orthogonal analyzer states that can be analyzed in the same way.

A.3 Calculations – Fourier transform

A Fourier analysis of $R(\lambda)$, usually expressed in the domain of optical frequency ν , is used to derive PMD. The Fourier transform transforms this optical frequency domain data to the time domain. The Fourier transform yields direct information on the distribution of light arrival times $\delta\tau$. These data are post-processed as described below to derive the expected PMD, $\langle\Delta\tau\rangle$, for the fibre under test. This method is applicable to links typically with random mode coupling. The method is however also applicable to negligible mode coupling.

A.3.1 Data pre-processing & Fourier transformation

To use this method, the Fourier transform normally requires equal intervals in optical frequency so that $R(\lambda)$ data are collected at λ values such that they form equal intervals in the optical frequency domain. Alternatively, data taken at equal λ intervals may be fitted (for example, by using a cubic spline fit) and interpolation used to generate these points, or more advanced spectral estimation techniques can be used. In each instance, the ratio $R(\lambda)$ at each λ value used is calculated using Equation (A.3) or Equation (A.4) as appropriate.

Zero-padding or data interpolation and DC level removal may be performed on the ratio data, $R(\lambda)$. Windowing the data may also be used as a pre-conditioning step before the Fourier transform. The Fourier transformation is now carried out, to yield the amplitude data distribution $P(\delta\tau)$ for each value of $\delta\tau$.

A.3.2 Transform data fitting

Fourier transform data at zero $\delta\tau$ has little meaning since, unless carefully removed, “dc” components in $R(\lambda)$ may be partially due to insertion loss of the analyzer for example. When the “dc” level is not removed, up to two data points are generally bypassed (not used) in any further calculations. A variable, j , can be defined so that the ‘first valid bin’ above zero $\delta\tau$ that is included in calculations corresponds to $j = 0$.

In order to remove measurement noise from subsequent calculations, $P(\delta\tau)$ is compared to a threshold level T_1 , typically set to 200 % of the RMS noise level of the detection system. It is now necessary to determine whether the fibre is negligibly or randomly mode coupled.

If it is found that the first X valid points of $P(\delta\tau)$ are all below T_1 , this indicates that $P(\delta\tau)$ shall have discrete spike features characteristic of negligibly coupled fibres. The value of X is equal to 3, unless zero-padding is used in the Fourier analysis. In that case, the value of X can be determined from:

$$X = \frac{3 \times (\text{number_original_data_points})}{\text{total_length_of_array_after_zeropadding}} \quad (\text{A.5})$$

PMD is calculated using Equation (A.6) for a negligible mode coupling fibre, or PMD is calculated using Equations (A.7a) and (A.7b) for a random mode coupling fibre.