

INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Optical fibres –
Part 1-48: Measurement methods and test procedures – Polarization mode
dispersion**

**Fibres optiques –
Partie 1-48: Méthodes de mesure et procédures d'essai – Dispersion de mode de
polarisation**



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INTERNATIONAL STANDARD

NORME INTERNATIONALE



Optical fibres –

Part 1-48: Measurement methods and test procedures – Polarization mode dispersion

Fibres optiques –

Partie 1-48: Méthodes de mesure et procédures d'essai – Dispersion de mode de polarisation

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

OPTICAL FIBRES –

**Part 1-48: Measurement methods and test procedures –
Polarization mode dispersion**

FOREWORD

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International Standard IEC 60793-1-48 has been prepared by subcommittee 86A: Fibres and cables, of IEC technical committee 86: Fibre optics.

This third edition cancels and replaces the second edition published in 2007. It constitutes a technical revision. This edition includes the following significant technical change with respect to the previous edition:

- a) removal of the SOP approach.

The text of this standard is based on the following documents:

CDV	Report on voting
86A/1678/CDV	86A/1766/RVC

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

This International Standard is to be read in conjunction with IEC 60793-1-1:2008. A list of all parts in the IEC 60793 series, published under the general title *Optical fibres*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

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INTRODUCTION

Polarization mode dispersion (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 narrow band 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 average of DGD values.

In long fibre spans, DGD is random in both 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 an average DGD value over an appropriately large optical frequency range, either RMS $\langle\Delta\tau\rangle$, the rms DGD over this frequency range, or MEAN $\langle\Delta\tau\rangle$, the (linear) mean of the DGD over this same frequency range. In principle, the average DGD value (RMS $\langle\Delta\tau\rangle$ or MEAN $\langle\Delta\tau\rangle$) 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, the average DGD value is a useful predictor of lightwave system performance.

The term "PMD" is used both in the general sense of two polarization modes having different group velocities, and in the specific sense of the average DGD value (RMS $\langle\Delta\tau\rangle$ or MEAN $\langle\Delta\tau\rangle$). Although the DGD $\Delta\tau$ or pulse broadening $\Delta\delta$ is preferably averaged over frequency, for certain situations it may be averaged over time, or temperature.

The coupling length l_c is the length of fibre or cable at which appreciable coupling between the two polarization states begins to occur. If the fibre length L satisfies the condition $L \ll l_c$, mode coupling is negligible, and $\langle\Delta\tau\rangle$ scales with fibre length. The corresponding PMD coefficient is

$$\text{short-length PMD coefficient} = \langle\Delta\tau\rangle/L.$$

Fibres in practical systems nearly always have fibre lengths much greater than the coupling length and random mode coupling. When mode coupling is random, $\langle\Delta\tau\rangle$ scales with the square root of fibre length, and

$$\text{long-length PMD coefficient} = \langle\Delta\tau\rangle/\sqrt{L}.$$

OPTICAL FIBRES –

Part 1-48: Measurement methods and test procedures – Polarization mode dispersion

1 Scope

This part of IEC 60793 applies to three methods of measuring polarization mode dispersion (PMD), which are described in Clause 4. It establishes uniform requirements for measuring the PMD of single-mode optical fibre, thereby assisting in the inspection of fibres and cables for commercial purposes.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 60793-1-1, *Optical fibres - Part 1-1: Measurement methods and test procedures - General and guidance*

IEC TR 61292-5, *Optical amplifiers - Part 5: Polarization mode dispersion parameter - General information*

ITU-T Recommendation G.650.2, *Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable*

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ITU-T Recommendation G.650.2 apply.

NOTE Further explanation of their use in this document is provided in IEC TR 61282-9.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.2 Symbols and abbreviated terms

Arg	Argument function
ASE	Amplified spontaneous emission
BBS	Broadband source
CFT	Cosine Fourier transform
c/c_0	Velocity of light in vacuum/in free space
DGD	Differential group delay
$DGD_{\max}$	Maximum DGD value

DOP	Degree of polarization
E	Number of extrema in $R(\lambda)$ (method A)
EC	Extrema counting
$f(\Delta\tau)$	Maxwell probability distribution
FA	Fixed analyser (method A)
FCFT	Fast cosine Fourier transform
FT	Fourier transform
FUT	Fibre under test
GINTY	General analysis for method C
INTY	Interferometry method (method C)
I/O	Input/output
JME	Jones matrix eigenanalysis (method B)
k	Mode coupling factor
l_c	Coupling length
L	Length of fibre/fibre cable test sample
LED	Light emitting diode
N	Total number of measurements/population of mode-coupled fibres/wavelength intervals
$P_A(\lambda)$	Optical power recorded with analyser in place (method A)
P_F	Probability of exceeding $DGD_{\max}$
$P_B(\lambda)$	Optical power recorded with analyser rotated 90 ° (method A)
$P_{\text{TOT}}(\lambda)$	Optical power recorded with analyser removed (method A)
$P_x(\tau)/P_y(\tau)$	Received power in the two orthogonal SOP axes corresponding to the fringes in method C
PBS	Polarization beam splitter
PDL	Polarization dependent loss
PDV	Polarization dispersion vector
PMD	Polarization mode dispersion
PMD_Q	Link design PMD value
PSA	Poincaré sphere analysis (method B)
PSP	Principle states of polarization
$R(\lambda)$	Output ratio from PMD measurement system (method A)
RBW	Resolution bandwidth
RTM	Reference test method
s	Normalized output Stokes vectors
SOP	State of polarization
SPE	Stokes parameter evaluation (method B)
T	Jones matrix
T^{-1}	Inverse of the Jones matrix
t_c	Optical source coherence time (method C)
TINTY	Traditional analysis for method C
α	Single parameter which specifies a Maxwell distribution
χ^2	Chi-squared variable

$\Delta \hat{h} / \Delta \hat{v} / \Delta \hat{q} / \Delta \hat{c}$	Finite differences computed from the Stokes vectors
$\delta \lambda$	Wavelength step size
$\Delta \lambda$	Optical source spectral width (full width half maximum (FWHM) unless otherwise noted)
$\delta \nu$	Optical frequency step size
$\Delta \theta$	Rotation angle on Poincaré sphere
$\delta \tau$	Arrival time of different polarization components of a signal or pulse broadening
$\Delta \delta \tau_{\max}$	Maximum $\delta \tau$ value that can be measured
$\Delta \delta \tau_{\min}$	Minimum $\delta \tau$ value that can be measured
$\Delta \tau$	DGD value
$\Delta \tau_{\max}$	Maximum DGD
$\langle \Delta \tau \rangle$	Average DGD over wavelength scan range or PMD value
$\sqrt{\langle \Delta \tau^2 \rangle}$	r.m.s. DGD over wavelength scan range or PMD value (method C)
$\langle \Delta \tau \rangle_0$	Maximum PMD specification that each fibre shall meet in a population of mode-coupled fibres
$\langle \Delta \tau \rangle_t$	Average DGD over time
$\langle \Delta \tau \rangle_T$	Average DGD over temperature
$\langle \Delta \tau \rangle_\lambda$	Average DGD over wavelength
$\Delta \omega$	Angular frequency variation in method B
λ	Test wavelength used to measure PMD
λ_0	Central wavelength of the light source
λ_1 / λ_2	First/last wavelength in set of test wavelengths (or position of first/last maximum or minimum in $R(\lambda)$ in method A)
ν	Optical light frequency
ρ_1 / ρ_2	Complex eigenvalues of $T(\omega + \Delta \omega) T^{-1}(\omega)$
σ	One-standard-deviation uncertainty
σ_0	r.m.s. width of the squared envelope of the autocorrelation interferogram (method C, GINTY)
σ_A	r.m.s. width of the autocorrelation envelope (method C)
σ_R	Second moment of FT data (method A)
σ_x	r.m.s. width of the squared envelope of the cross-correlation interferogram (method C, GINTY)
σ_ε	r.m.s. width of the cross-correlation envelope (method C, TINTY)
ω	Angular optical frequency
Ω	PDV

4 General

4.1 Methods for measuring PMD

Three methods are described for measuring PMD (see Annexes A, B and C for more details). The methods are listed below in the order of their introduction. For some methods, multiple approaches of analysing the measured results are also provided.

- a) Method A
 - 1) Fixed analyser (FA)
 - 2) Extrema counting (EC)
 - 3) Fourier transform (FT)
 - 4) Cosine Fourier transform (CFT)
- b) Method B
 - 1) Stokes parameter evaluation (SPE)
 - 2) Jones matrix eigenanalysis (JME)
 - 3) Poincaré sphere analysis (PSA)
- c) Method C
 - 1) Interferometry (INTY)
 - 2) Traditional analysis (TINTY)
 - 3) General analysis (GINTY)

The PMD value is defined in terms of the differential group delay (DGD), $\Delta\tau$, which usually varies randomly with wavelength, and is reported as one or another statistical metric. Equation (1) is a linear average value of the DGD values and is used for the specification of optical fibre cable. Equation (2) is the root mean square value which is reported by some methods. Equation (3) can be used to convert one value to the other if the DGDs are assumed to follow a Maxwell random distribution.

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

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

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

Equation (3) applies only when the distribution of DGDs is Maxwellian, for instance when the fibre is randomly mode coupled. The generalized use of Equation (3) can be verified by statistical analysis. A Maxwell distribution may not be the case if there are point sources of elevated birefringence (relative to the rest of the fibre), such as a tight bend, or other phenomena that reduce the mode coupling, such as a continual reduced bend radius with fibre in tension. In these cases, the distribution of the DGDs will begin to resemble the square root of a non-central Chi-square distribution with three degrees of freedom. For these cases, the PMD_{RMS} value will generally be larger relative to the PMD_{MEAN} that is indicated in Equation (3). Time domain methods such as method C and method A, cosine Fourier transform, which are based on PMD_{RMS} , can use Equation (3) to convert to PMD_{MEAN} . If mode coupling is reduced, the resulting reported PMD value from these methods can exceed those that can be reported by the frequency domain measurements that report PMD_{MEAN} , such as method B.

The PMD coefficient is the PMD value normalized to the fibre length. For normal transmission fibre, for which random mode coupling occurs and for which the DGDs are distributed as Maxwell random variables, the PMD value is divided by the square root of the length, and the PMD coefficient is reported in units of $\text{ps}/\sqrt{\text{km}}$. For some fibres with negligible mode coupling, such as polarization maintaining fibre, the PMD value is divided by the length, and the PMD coefficient is reported in units of ps/km .

All methods are suitable for laboratory measurements of factory lengths of optical fibre and optical fibre cable. For all methods, changes in the deployment of the specimen can alter the results. For installed lengths of optical fibre cable that may be moving or vibrating, either method C or method B is appropriate (in an implementation capable of millisecond measurement time scales).

All methods require light sources that are controlled at one or more states of polarization (SOPs). All methods require injecting light across a broad spectral region (i.e. 50 nm to 200 nm wide) to obtain a PMD value that is characteristic of the region (i.e. 1 300 nm or 1 550 nm). The methods differ in:

- a) the wavelength characteristics of the source;
- b) the physical characteristics that are actually measured;
- c) the analysis methods.

Method A measures PMD by measuring a response to a change of narrowband light across a wavelength range. At the source, the light is linearly polarized at one or more SOPs. For each SOP, the change in output power that is filtered through a fixed polarization analyser, relative to the power detected without the analyser, is measured as a function of wavelength. The resulting measured function can be analysed in one of three ways:

- a) by counting the number of peaks and valleys (EC) of the curve and application of a formula that has been shown [1]¹ to agree with the average of DGD values, when the DGDs are distributed as Maxwellian. This analysis is considered as a frequency domain approach;
- b) by taking the FT of the measured function. This FT is equivalent to the pulse spreading obtained by the broadband transmission of method C. Appropriate characterisation of the width of the FT function agrees with the average of DGD values, when the DGDs are distributed as Maxwellian;
- c) by taking the CFT of the difference of the normalized spectra from two orthogonal analyser settings and calculating the r.m.s. of the squared envelope. The PMDRMS value is reported. This is equivalent to simulating the fringe pattern of the cross-correlation function that would result from interferometric measurements.

Method B measures $\Delta\tau(\omega)$ by measuring a response to a change of narrowband light across a wavelength range. At the source, the light is linearly polarized at one or more SOPs. The Stokes vector of the output light is measured for each wavelength. The change of these Stokes vectors with angular optical frequency, ω , and with the (optional) change in input SOP yields the DGD as a function of wavelength through relationships that are based on the following definitions:

$$\frac{ds(\omega)}{d\omega} = \Omega(\omega) \times s(\omega) \quad (4)$$

$$\Delta\tau(\omega) = |\Omega(\omega)| \quad (5)$$

where

s is the normalized output Stokes vector;

Ω is the polarization dispersion vector (PDV) in the direction of the PSPs;

$\Delta\tau$ is the DGD.

For both the JME and PSA analysis approaches, three linear SOPs at nominally 0 °, 45 °, and 90 ° (orthogonal on the Poincaré sphere) shall be launched for each wavelength.

¹ Numbers in square brackets refer to the Bibliography

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

The PSA approach is completed by doing matrix algebra on the normalized output Stokes vectors to infer the rotation of the output Stokes vector on the Poincaré sphere at two adjacent wavelengths, using the application of an arcsine formula to obtain the DGD. The JME and PSA approaches are mathematically equivalent for common assumptions (see IEC TR 61282-9).

Method C is based on a broadband light source that is linearly polarized. The cross-correlation of the emerging electromagnetic field is determined by the interference pattern of output light, i.e. the interferogram. The determination of the PMD delay for the wavelength range associated with the source spectrum is based on the envelope of the fringe pattern of the interferogram. Two analyses are available to obtain the PMD delay (see IEC TR 61282-9), both of which measure the PMD_{RMS} value:

- a) TINTY uses a set of specific operating conditions for its successful applications and a basic setup;
- b) GINTY uses no limiting operating conditions but, in addition to the same basic set-up as TINTY, it uses a modified setup.

The analysis approaches represent an evolution of the understanding of PMD. The GINTY is, for example, more complete than TINTY. The reproducibility of PMD depends on the PMD level and the wavelength range of the measurement [3]. Better relative reproducibility is achieved for broader wavelength ranges and higher PMD values for a given range. For measurements of higher PMD values, for example 0,5 ps, the differences in the analysis methods are less important than for the measurements of low PMD values.

Information common to all three methods is contained in Clauses 4 to 10, and requirements pertaining to each individual method appear in Annexes A, B, and C, respectively. IEC TR 61282-9 provides the mathematical formulations for all methods.

4.2 Reference test method

Method B is the reference test method (RTM), which shall be the one used to settle disputes.

4.3 Applicability

PMD in fibre is a statistical parameter. IEC 60794-3 includes a statistical requirement on PMD, called PMD_Q or link design value that is based on sampled measurements of optical fibre cable and calculations for concatenated links. The PMD of a cabled fibre can vary from the PMD of the uncabled fibre due to effects of cable construction and processing. A limit on the PMD_Q of the uncabled fibre is, however, required to limit the PMD_Q on cabled fibre. Uncabled fibre PMD_Q less than half the cabled fibre PMD_Q limit is generally considered as a conservative rule. Alternative limits may be determined for particular constructions and stable cable processes.

The fibre or cable deployment should be selected so that externally induced mode coupling is minimized. Sources of such external mode coupling can be:

- a) excessive tension;
- b) excessive bending induced from
 - 1) fibre cross-overs on a shipping reel;
 - 2) crimping of fibre within a cable on a spool that is too small;
 - 3) too small a bend radius.
- c) excessive twist.

Reproducibility of individual measurements should be evaluated after perturbing the fibre to allow sampling the full range of mode coupling combinations. This can be done by, for example, changing the temperature slightly or making small adjustments in the deployment. Gisin [3] reported a fundamental relative reproducibility limit for measurements and showed that the relative reproducibility improves as the PMD increases and as the spectral width of the source increases. When PMD measurements are combined to evaluate the statistical specification of optical fibre cable (see IEC 60794-3), this variability leads to a possible overstatement of the link design value.

Guidelines for the calculation of PMD for systems that include other components such as dispersion compensators or optical amplifiers are given in IEC TR 61282-3. Test methods for optical amplifiers are given in IEC 61290-11-1 and IEC 61290-11-2, and other design guides in IEC TR 61292-5. Test methods for testing links, including amplified ones, are given in IEC 61280-4-4. Test methods for optical components are given in IEC 61300-3-32. General information about PMD, the mathematical formulation related to the application of the present methods, and some considerations related to the sampling theory related to the use of different light sources and detection systems are given in IEC TR 61282-9.

5 Apparatus

5.1 General

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

5.2 Light source and polarizers

See Annexes A, B, and C 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. IEC TR 61282-9 provides additional guides concerning the source input SOP, degree of polarization (DOP), use of polarizers and polarization controllers.

5.3 Input optics

An optical lens system or fibre pigtail may be employed to excite the specimen. It is recommended that the power coupled into the specimen be relatively insensitive to the position of its input end face. This can be accomplished by using a launch beam that spatially and angularly overfills the input end face.

If using a butt splice, employ index-matching material between the fibre pigtail and the specimen to avoid interference effects. The coupling shall be stable for the duration of the measurement.

5.4 Input positioner

Provide means of positioning the input end of the specimen to the light source. Examples include the use of x-y-z micropositioner stages, or mechanical coupling devices such as connectors, vacuum splices, three-rod splices, etc. The position of the fibre shall remain stable over the duration of the measurement.

5.5 Cladding mode stripper

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

5.6 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 (see IEC 60793-1-44) of the specimen. For example, a one-turn bend of radius of 30 mm on the fibre is generally sufficient.

5.7 Output positioner

Provide a suitable means for aligning the fibre output end face to the output optics. Such coupling may include the use of lenses, or may be a mechanical connector to a detector pigtail.

Provide means such as a side-viewing microscope or camera with a crosshair to locate the fibre at a fixed distance from the output optics. It may be sufficient to provide only longitudinal adjustment if the fibre is constrained in the lateral plane by a device such as a vacuum chuck.

5.8 Output optics

See Annex A, B, or C, as appropriate.

5.9 Detector

For signal detection, an optical detector is used which is linear and stable over the range of intensities 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, an optical spectrum analyser, or a polarimeter. To use the entire spectral range of the source, the detection system shall have a wavelength range that includes the wavelengths produced by the light source. See Annex A, B, or C, as appropriate, for additional details.

5.10 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 Sampling and specimens

6.1 General

A specimen is a known length of single-mode optical fibre (IEC 60793-2-50) which may or may not be cabled. The sample and pigtails shall be fixed in position at a nominally constant temperature throughout the measurement. Standard atmospheric conditions are defined in IEC 60793-1-1 and shall be employed unless otherwise specified. In the case of installed fibres and cables, prevailing deployment conditions may be used.

Mechanical and temperature stability of the test device may be observed by the following procedures. For method A, the output power from the fibre at a fixed wavelength is measured with the output analyser in place. In a time period corresponding to a typical complete measurement, the output power change should be small relative to the changes produced by a wavelength increment. For method B, the output SOP of the test fibre on a Poincaré sphere display is viewed. In a time period corresponding to an adjacent pair of Jones matrix measurements, the output SOP change should be small relative to the change produced by a wavelength increment. Method C is normally robust with regard to slight temperature change or fibre movements.

End faces for the input and output ends of the test sample shall be prepared as appropriate for the requirements of the apparatus and procedure. Precautions shall be taken to avoid any reflections.

6.2 Specimen length

The specimen length is dictated by three factors:

- a) minimum desired PMD coefficient;
- b) mode coupling regime;
- c) signal to noise ratio.

Each test method and implementation is limited to a minimum PMD value (ps) that can be measured. In many cases, this minimum can be determined based on theory. It can also be determined experimentally by examining the measured distribution. For fibres in the random mode coupling regime, the minimum PMD coefficient is determined by dividing the PMD value by the square root of the fibre length (km). For the negligible mode coupling case, the division is by the length. The length that is measured and the minimum measurable PMD value will therefore determine the minimum measurable PMD coefficient. Fibres or cables with lengths sufficient to achieve this minimum can be selected for measurement. Alternatively, specimens can be cut to a satisfactory length. The minimum measurable PMD value shall be documented. The length of the individual specimens shall be recorded. The length can also be limited by the deployment method (see 6.3) and instrument dynamic range.

The values specified in IEC 60794-3 and IEC 60793-2-50 express the PMD coefficient in terms of $\text{ps}/\sqrt{\text{km}}$. In effect, these documents assume that the length measured is sufficient to induce the randomly mode-coupled regime. For a given fibre type or cable construction, this can be confirmed by doing a cut-back experiment in which the PMD value is measured on a specimen at each of several lengths achieved by cutting the specimen back between measurements. Lengths above which there is a square root dependence of the PMD value on length may be considered as randomly mode-coupled.

The dynamic range is limited by the method, the source power, and the overall loss of the specimen, which is affected by length. This limit shall generally be determined based on of specific implementations by experimental means. This limit shall be documented.

6.3 Deployment

6.3.1 General

The deployment of the fibre or cable can influence the result. For normal measurements to be used in specification conformance evaluation, the following requirements apply.

6.3.2 Uncabled fibre

It is important to minimize deployment-induced mode coupling when measuring uncabled fibres, which is done in order to support the primary requirements of cabled fibre PMD_Q . In this case, the fibre shall be supported in some manner (usually on a reel having a minimum wind radius of 150 mm), with essentially zero fibre tension (typically less than 5 g), and no tensioned crossovers. These deployment requirements can limit the length that can be measured, depending on the spool diameter, and can make the measurement a destructive one. Multi-layer windings are possible, but should be qualified by comparison to single-layer results on shorter lengths.

The measurement of uncabled fibre deployed on shipping spools is not recommended. PMD results with this deployment have been shown to be substantially less than what would be obtained in cable form for high PMD fibre and substantially greater than what would be obtained in cable form for low PMD fibre.

6.3.3 Optical fibre cable

PMD measurements on fibres in cables wound on shipping drums cannot always reflect the functionally relevant PMD values for fibres in the installed cable deployment configuration.

Consequently, to demonstrate compliance with the cabled-fibre PMD specification, alternative deployment configurations or mapping functions relating on-drum PMD value to off-drum PMD value can be used for factory measurements. The exact deployment configuration shall be agreed upon between the supplier and the customer.

7 Procedure

The procedure is as follows:

- a) Deploy the fibre or cable and prepare the ends.
- b) Attach the ends to the input and output optics.
- c) Engage the computer to complete the scans and measurements found in Annexes A, B, and C for the three measurement methods.
- d) Complete documentation.

8 Calculation or interpretation of results

Annexes A, B, and C provide calculations to convert the measured data into PMD values. The calculation of the PMD coefficient is carried out according to whether random mode coupling or negligible mode coupling is present. For the fibres specified in IEC 60793-2-50, the PMD value is normalized by the square root of the fibre length in units of $\text{ps}/\sqrt{\text{km}}$.

9 Documentation

9.1 Information required for each measurement

- a) Specimen identification;
- b) Testing date;
- c) Specimen length;
- d) Wavelength region (for example, 1 550 nm);
- e) PMD in units of ps, and whether PMD_{MEAN} or PMD_{RMS} is reported;
- f) PMD coefficient and its units ($\text{ps}/\sqrt{\text{km}}$ or ps/km).

9.2 Information to be available

- a) Measurement method used;
- b) Calculation approach used;
- c) Description of the deployment method (including any fibre support mechanism);
- d) Wavelength range used;
- e) For methods A and B with a narrowband source and a step mode, the number of wavelengths sampled;
- f) For method C, the type of fringe-detection technique;
- g) Description of the equipment;
- h) Date of latest calibration;
- i) Evidence supporting the mode coupling regime (indicated by units of the PMD coefficient);
- j) For method B with narrowband source and a step mode, the wavelength range resolution;
- k) For method B with broadband source (BBS), the centre wavelength and -3 dB linewidth.
- l) Any deviations from this procedure

10 Specification information

- a) Type of fibre or cable;
- b) Failure or acceptance criteria.

Annex A (normative)

Requirements specific to method A (FA) – Fixed analyser measurement method

A.1 Apparatus

A.1.1 Block diagrams

Figure A.1 shows possible block diagrams for method A.

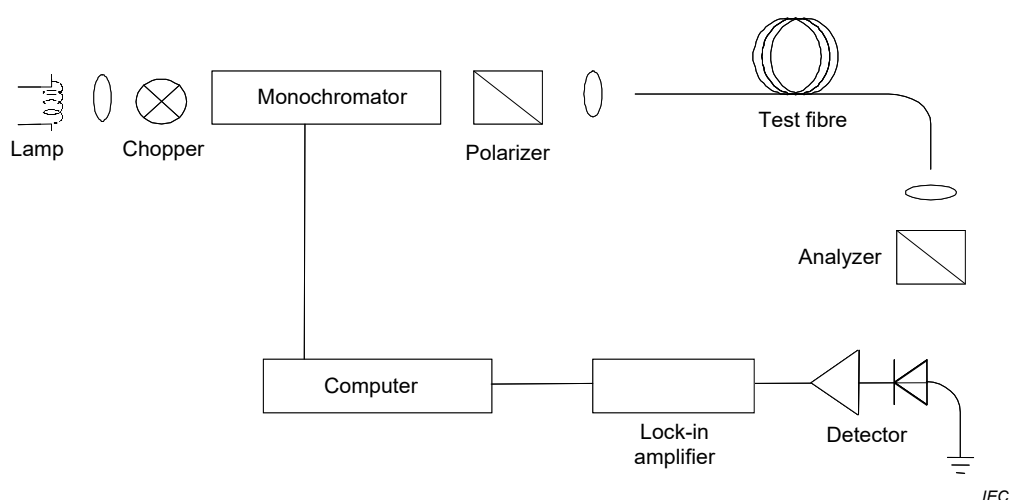


Figure A.1a – Narrowband source

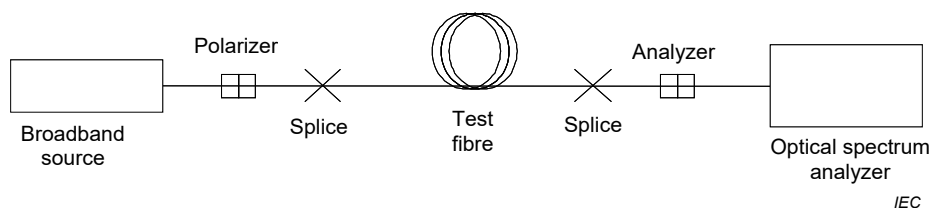


Figure A.1b – Broadband source

Figure A.1 – Block diagrams for method A

A.1.2 Light source

In all cases, two kinds of light sources may be used, depending on the type of analyser. A narrowband source such as the broadband lamp and monochromator combination shown in Figure A.1a can be used with a polarization analyser. A BBS shown in Figure A.1b can be used with a narrow bandpass filtering analyser such as an optical spectrum analyser or an interferometer used as a FT spectrum analyser placed before the analyser. In the case of BBS, 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 degree of polarization (see 4.1). In both cases, the range of wavelengths shall be sufficient to provide a PMD measurement of sufficient precision at the specified wavelength region (see Clause A.3).

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

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

where

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

$\Delta\lambda$ is the spectral width;

$\Delta\tau_{\max}$ 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.1.3 Analyser

The angular orientation of the analyser is not critical but should remain fixed throughout the measurement. With negligible mode coupling or low PMD values, some adjustment of the analyser may be helpful in maximising the amplitude of the oscillations in Figure A.2 – which can also be achieved by rotating the fibre at splices or connectors. For the CFT approach, the analyser shall be capable of being rotated to a setting that is orthogonal to the initial setting.

NOTE The analyser 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 or optical frequency increment once with the analyser in the optical path and once without – or once with the analyser in the optical path and once with the analyser set to a position orthogonal to the initial setting. The wavelength range can influence the precision of the result (see Clause A.3). The wavelength increment should be selected to satisfy Equation (A.1), with the wavelength increment replacing $\Delta\lambda$.

If the FT or CFT approaches are used, the step size 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 randomly mode-coupled fibres, the Nyquist condition shall be at least three times the frequency of the second moment for the maximum anticipated DGD. That is:

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

If, from the FT, it is evident that there is significant energy near $\Delta\tau_{\max}$, the measurement should be repeated with a reduced increment. 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 analyser in the light path. Record the received power as $P_{\lambda}(\lambda)$.

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

Calculate the power ratio, $R(\lambda)$ as follows. Figure A.2 shows an example of both negligibly and randomly mode-coupled results.

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

An alternative procedure is to leave the analyser 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 ratio, P_A/P_B , can also be used when extrema counting is used.

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

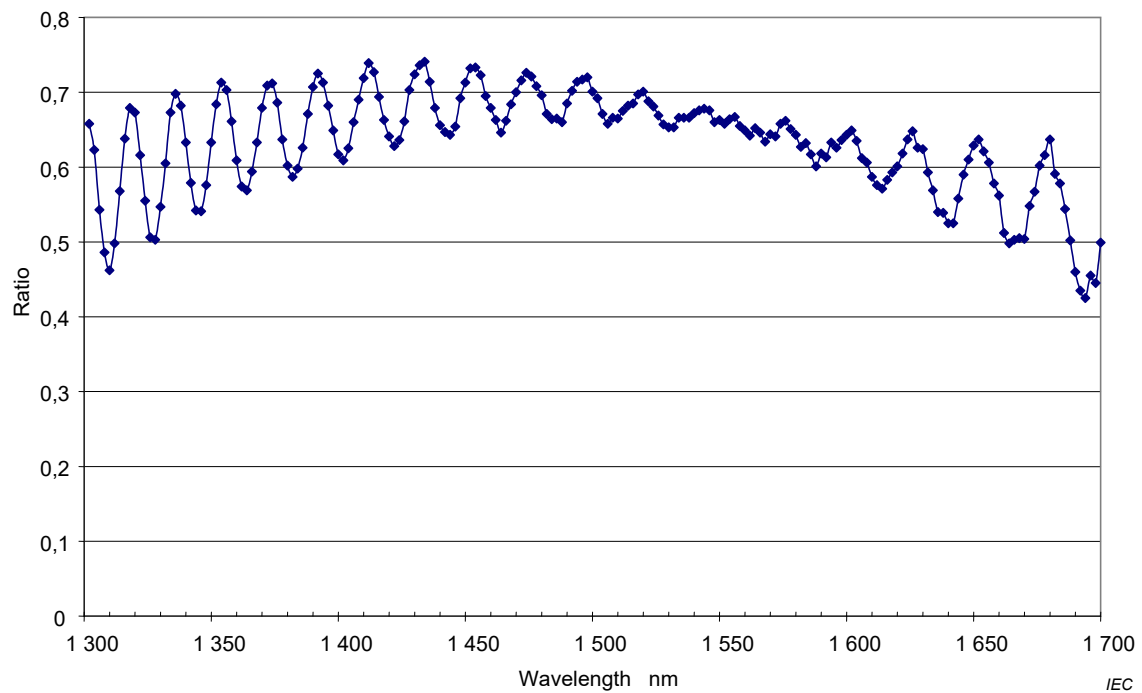


Figure A.2a – Negligible mode coupling

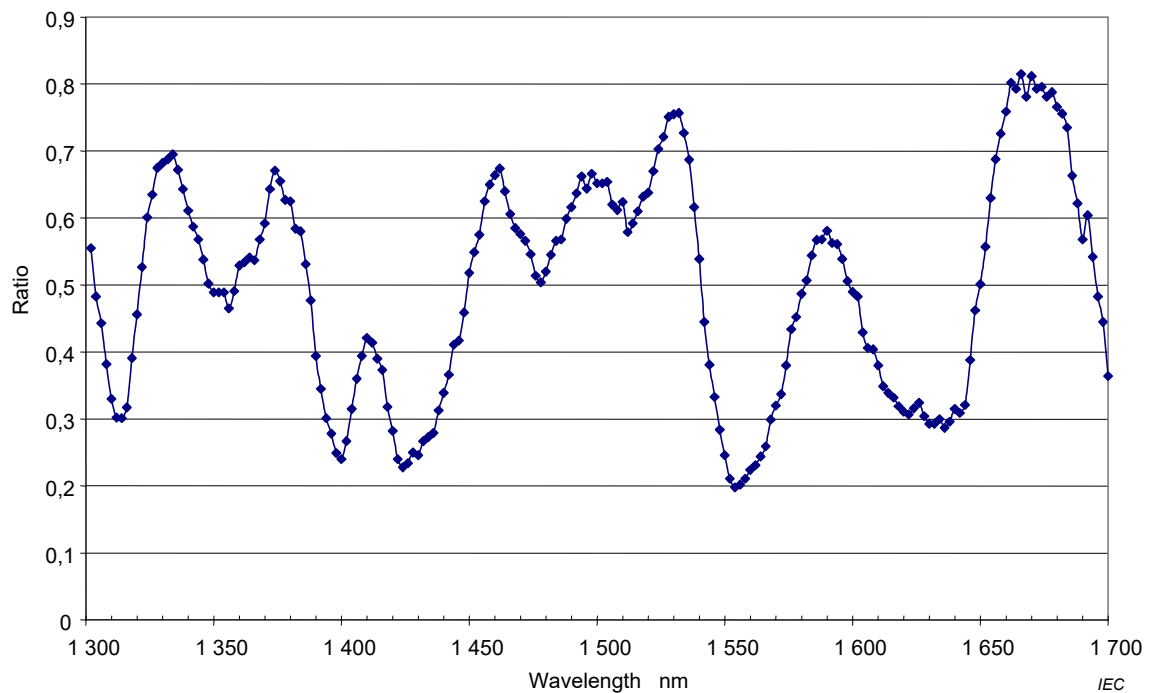


Figure A.2b – Random mode coupling

Figure A.2 – Typical results from method A

A.3 Calculations

A.3.1 Approaches of calculating PMD

There are three approaches of calculating PMD from the R function that is measured:

- a) extrema counting;
- b) Fourier transform;
- c) cosine Fourier transform.

A.3.2 Extrema counting

The function, $R(\lambda)$, should be obtained at equally spaced wavelength intervals from a minimum wavelength of λ_1 to a maximum wavelength of λ_2 . E is the number of extrema (both maxima and minima) within the window. Alternatively, the wavelength range can be redefined so that λ_1 and λ_2 coincide with extrema, in which case E is the number of extrema (including λ_1 and λ_2) minus one. The formula for the PMD value, $\langle \Delta\tau \rangle$, is:

$$\langle \Delta\tau \rangle = \frac{kE\lambda_1\lambda_2}{2c(\lambda_2 - \lambda_1)} \quad (\text{A5})$$

where

c is the speed of light in vacuum;

k is a mode coupling factor which equals 1,0 in the absence of random mode coupling and 0,82 in the limit of random mode coupling.

If a polarimeter is used as the detection element, the average of the values derived from the three normalised Stokes parameter responses is taken as the final value of PMD.

In the presence of noise, the extrema can be difficult to determine. One solution is to fit the data to a running polynomial that can be evaluated for extrema at every point. A cubic polynomial that covers eight wavelengths has been used successfully.

A.3.3 Fourier transform

A.3.3.1 General

In this method, a Fourier analysis of $R(\lambda)$, usually expressed in the optical frequency domain 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 $\delta\tau$. This data is post-processed as described below to derive the expected PMD, $\langle \Delta\tau \rangle$, for the fibre under test. This method is applicable to fibres with negligible or random mode coupling.

A.3.3.2 Data pre-processing and 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 transform is now carried out, to yield the amplitude data distribution $P(\delta\tau)$ for each value of $\delta\tau$.

A.3.3.3 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 analyser 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 three, unless zero-padding is used in the Fourier analysis. In that case, the value of X can be determined from three times the number of original data points divided by the total length of the array after zero-padding.

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

A.3.3.4 PMD calculation for fibres with negligible mode coupling

For a negligibly coupled fibre (e.g., a high birefringence fibre) or for a birefringent component, $R(\lambda)$ resembles a chirped sine wave (Figure A.2a). Fourier transform will give a $P(\delta\tau)$ output containing a discrete spike at a position corresponding to the relative pulse arrival time, $\delta\tau$, the centroid of which is the PMD value $\langle\Delta\tau\rangle$.

To define the spike centroid $\langle\Delta\tau\rangle$, those points where $P(\delta\tau)$ exceeds a second pre-determined threshold level T_2 , typically set to 200 % of the RMS noise level of the detection system, are used in the equation:

$$\langle\Delta\tau\rangle = \frac{\sum_{e=0}^{M'} [P_e(\delta\tau)\delta\tau_e]}{\sum_{e=0}^{M'} P_e(\delta\tau)} \quad (\text{A.6})$$

where

$M' + 1$ is the number of data points of P within the spike which exceed T_2 .

In Equation (A.6), $\langle\Delta\tau\rangle$ is typically quoted in picoseconds. If no spike is detected (i.e., $M' = 0$), then PMD is zero. Other parameters such as the RMS spike width and/or spike peak value may be reported.

If the device under test contains one or more birefringent elements, more than one spike will be generated. For a number n concatenated fibres/devices, up to $2^{(n-1)}$ spikes will be obtained.

A.3.3.5 PMD calculation for fibres with random mode coupling

In instances of random mode coupling, $R(\lambda)$ becomes a complex waveform similar to Figure A.2b, the exact characteristics being based on the actual statistics of the coupling process within the fibre/cable. The Fourier transformed data now becomes a distribution $P(\delta\tau)$ representing the combination of autocorrelation and cross-correlation functions of light pulse arrival times, $\delta\tau$, in the fibre (see Figure A.3).

Counting up from $j = 0$, the first point of P is determined which exceeds T_1 , and which is followed by at least X data points which fall below T_1 . This point represents the last significant point in (i.e., the 'end' of) the distribution $P(\delta\tau)$, for a randomly mode-coupled fibre that is not

substantially affected by measurement noise. The $\delta\tau$ value for this point is denoted $\delta\tau_{\text{last}}$, and the value of j at $\delta\tau_{\text{last}}$ is denoted M'' .

The square root of the second moment, σ_R , of this distribution defines the fibre PMD $\langle\Delta\tau\rangle$, and is given by:

$$\langle\Delta\tau\rangle = \sigma_R = \sqrt{\left\{ \sum_{j=0}^{M''} [P_j(\delta\tau) \delta\tau_j^2] / \sum_{j=0}^{M''} [P_j(\delta\tau)] \right\}} \quad (\text{A.7})$$

A.3.3.6 PMD calculation for mixed coupling fibre systems

There may be instances where both negligibly coupled fibre/components and randomly coupled fibre(s) are concatenated to form the system under test. In this case, both centroid determination (Equation (A.6)) and the second moment derivation (Equation (A.7)) may be required. Note that spikes in $P(\delta\tau)$ may only be determined beyond the $\delta\tau_{\text{last}}$ computed.

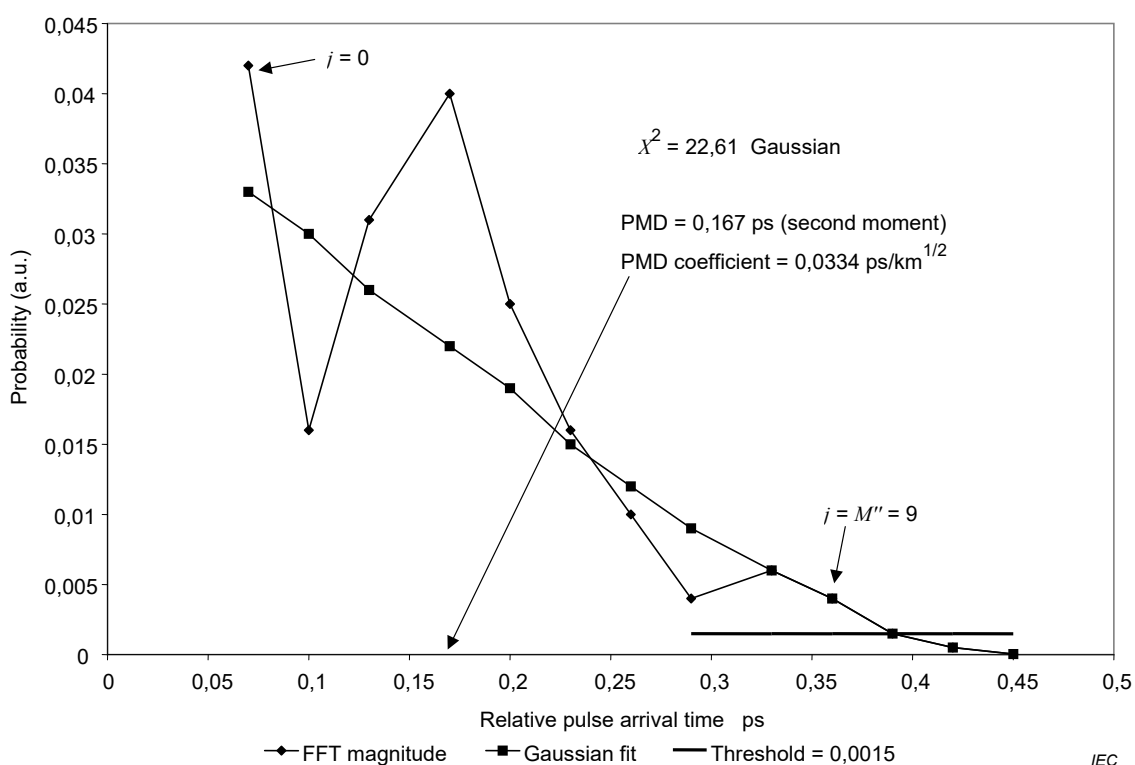


Figure A.3 – PMD by Fourier analysis

A.3.4 Cosine Fourier analysis

A.3.4.1 General

This analysis is based on the observation that the cosine Fourier transform of the spectrum emitted from the analyser is the fringe pattern of the interferogram that would be obtained from method C. The difference between fringe patterns generated by the analyser being set at two orthogonal settings is the cross-correlation function. For an infinite spectrum into the analyser, the autocorrelation function would have zero width. In practice, the finite source spectrum in the optical frequency domain acts as a windowing function which produces a non-zero autocorrelation function width in the time domain.

The analysis of the squared cross-correlation and autocorrelation functions found in the method C, GINTY analysis [4] shows that the difference in squared RMS widths of these

functions is proportional to the square of the spectrally weighted RMS (by squared power) of the DGD values (see Equation (C.9)) .

The result is independent of the spectral shape which means that the details of the windowing function are fully taken into account. It is also independent of the degree of mode coupling, which means that no changes in algorithm are needed to treat the different mode coupling regimes.

The result is limited by the spectral width and optical frequency increment that is measured. As the PMD increases, the frequency increment shall be decreased. At some limit it would be more practical to use the method C (GINTY).

The analysis reports the PMD_{RMS} metric. If random mode coupling is present, the result can be converted to PMD_{MEAN} using Equation (3).

A.3.4.2 Overview

The measurement of the powers emitted from the analyser set at two orthogonal settings is required. The ratio, R , associated with Equation (A.4) is modified to:

$$R(\nu) = \frac{P_A(\nu) - P_B(\nu)}{P_A(\nu) + P_B(\nu)} \quad (A.8)$$

where

$\nu = c / \lambda$ is the optical frequency (THz).

If a polarimeter is used, the three normalized output Stokes vector elements are equivalent to three independent normalized ratios equivalent to that represented by Equation (A.8). Each Stokes vector element is the difference in powers between orthogonal analyser settings. The three elements are different in that the base settings are also orthogonal.

The data is multiplied by a windowing function, $W(\nu)$, that goes to zero smoothly at the edges. Both $R(\nu)W(\nu)$ and $W(\nu)$ are put into arrays with zero padding at lower, unmeasured frequencies. Fast cosine Fourier transforms (FCFT) are applied to each array to obtain the time domain fringe envelopes, $r(t)w(t)$ and $w(t)$. These are squared to obtain the squared cross-correlation and autocorrelation envelopes, E_x^2 and E_0^2 , respectively. When multiple ratio functions (N) are available from different combinations of input polarizer setting and base analyser settings (or different Stokes output vector elements), using for instance input/output SOP scrambling, form the mean square envelopes as:

$$\overline{E_x^2} = \frac{1}{N} \sum_i E_{xi}^2 \quad (A.9)$$

$$\overline{E_0^2} = \frac{1}{N} \sum_i E_{0i}^2 \quad (A.10)$$

Using the RMS calculation of Annex D.2, calculate the RMS widths, σ_x and σ_0 of these two functions. The PMD_{RMS} value is calculated as:

$$PMD_{RMS} = \sqrt{\left[\frac{3}{2} (\sigma_x^2 - \sigma_0^2) \right]} \quad (A.11)$$

It is related to the spectrally weighted (by squared window value) RMS of the DGDs as:

$$\langle PMD_{RMS} \rangle = \frac{\int \Delta\tau^2(\nu) W^2(\nu) d\nu}{\int W^2(\nu) d\nu} \quad (A.12)$$

The expected value operator is with respect to random input/output SOPs.

A.3.4.3 Details

This subclause explains some of the details with respect to the measured frequency window, the frequency increment, $\Delta\nu$, frequency shifting, and the result of the FCFT. An example of a FCFT algorithm may be found in [5].

The data shall be available in uniform frequency increments. The number of data points, including zero pad values, shall be $1+2^k$, with k an integer.

If the N measured data points are not taken in uniform frequency increments, they may be fitted to a polynomial such as a spline for interpolation. A cubic spline [6] with $N - 3$ uniform segments will fit all the data perfectly and allow interpolation.

Given that the measured data are bounded by $\nu_{\min M}$ and $\nu_{\max M}$ and the fact that the minimum optical frequency is well above zero, the application of frequency shifting can be used to reduce the size of the arrays that are processed. The boundaries of the frequencies used in the calculation array can be selected by any choice of n such that:

$$\nu_{\max} \frac{n-1}{n} = \nu_{\min} \leq \nu_{\min M}, \quad \nu_{\max} = \nu_{\max M}, \quad \text{and } n \text{ is a positive integer.} \quad (A.13)$$

The frequency values less than the measured frequency are filled with zeros.

Following the FCFT, the array will contain the time domain fringe pattern from times of 0 to $t_{\max} = \Delta t 2^k$, where the time increment, Δt , is given as:

$$\Delta t = \frac{n}{2\nu_{\max}} = \frac{1}{2(\nu_{\max} - \nu_{\min})} \quad (A.14)$$

The fringe pattern that would be obtained from interferometry extends to negative time values as well as positive time values. The value at a given negative time is equal to the value at the positive time. The function is even and symmetric about zero.

The selection of the frequency shift should be done keeping in mind that the RMS width calculation needs some time domain values that are less than the minimum PMD_{RMS} that is measurable.

The frequency increment, $\Delta\nu$, is also related to the number of points sampled, the frequency shift, and the maximum PMD_{RMS} that is to be measured. It is given as the following, along with the constraint as:

$$\Delta\nu = \frac{\nu_{\max} - \nu_{\min}}{2^k} \leq \frac{1}{24 PMD_{RMS-\max}} \quad (A.15)$$

The spectral width of the filtered source should be half of this value. When the actual scan is done in equal wavelength increments, the wavelength increment at the lower end of the range should be consistent with the constraint of Equation (A.14).

The windowing function, $W(v)$, can technically be any function, including a square function. The function that is chosen should be one that minimizes the value of σ_0 . Functions that do this proceed to zero at the edges in a continuous way and should have the first derivative proceed to zero at the edges. This will minimize the ringing that can increase σ_0 .

A.3.4.4 Examples

Table A1 shows a sample calculation spreadsheet. The wavelength extrema and k are entered. For each of several possible frequency shift values, n , the other parameters are calculated. minPMD is calculated as $3\Delta t$. The increment in terms of $\Delta\lambda$ at the lower wavelength limit is also presented. Clearly, there are trade-offs, depending on the range of PMD_{RMS} values that are to be measured. In general, the broader the wavelength range and the smaller the frequency increment, the better.

Table A.1 – Cosine transform calculations

c	299792,5	nm/ps				
k	11					
npt	2048					
wavelengths (nm)		frequencies (THz)				
max	1700	230,6096				
min	1300	176,3485				
Frequency shift						
n	freqmincalc (THz)	del-t (ps)	delfreq (THz)	minPMD (ps)	maxPMD (ps)	wave increment (nm)
1	0	0,002168	0,112602	0,006504	0,370034	0,635076
2	115,3048077	0,004336	0,225205	0,013009	0,185017	1,270772
3	153,7397436	0,006504	0,337807	0,019513	0,123345	1,90709
4	172,9572115	0,008673	0,450409	0,026018	0,092508	2,544031
5	184,4876923	0,010841	0,563012	0,032522	0,074007	3,181596
6	192,1746795	0,013009	0,675614	0,039027	0,061672	3,819785
7	197,6653846	0,015177	0,788216	0,045531	0,052862	4,458599
8	201,7834135	0,017345	0,900819	0,052036	0,046254	5,098039

Figure A.4 illustrates the results for what might be obtained from a fibre with $PMD_{RMS} = 0,2$ ps. The mean cross-correlation and mean autocorrelation envelopes from a single scan using a windowing function that is Gaussian with a standard deviation of 23 nm are shown. The result is from a simulation of a fibre with ideal random mode coupling. The measured result for this simulation was 0,185 ps.

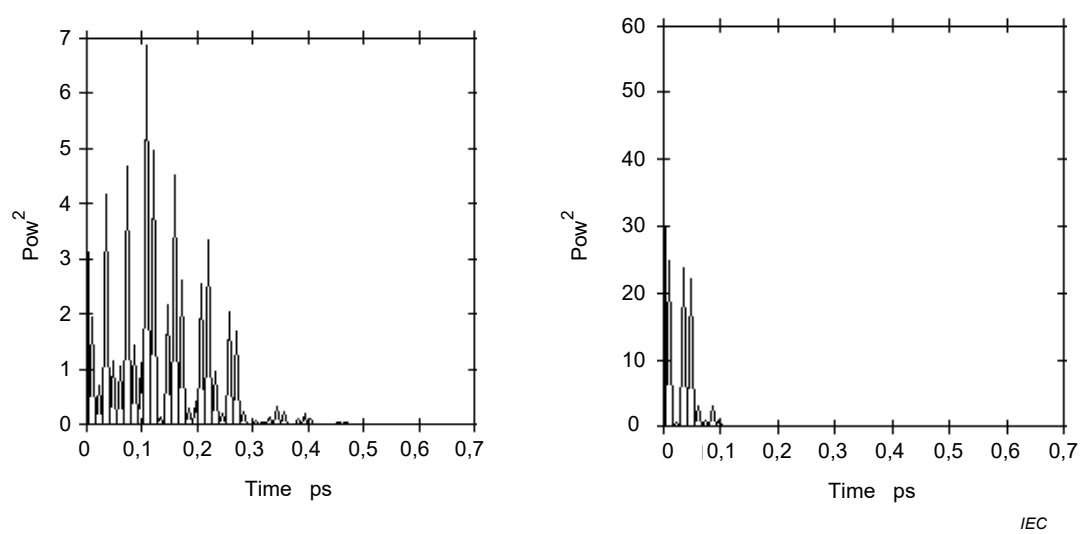


Figure A.4 – Cross-correlation and autocorrelation functions

Annex B (normative)

Requirements specific to method B (SPE) – Stokes parameter evaluation method

B.1 Apparatus

B.1.1 Block diagram

Figure B.1 shows a possible block diagram for method B.

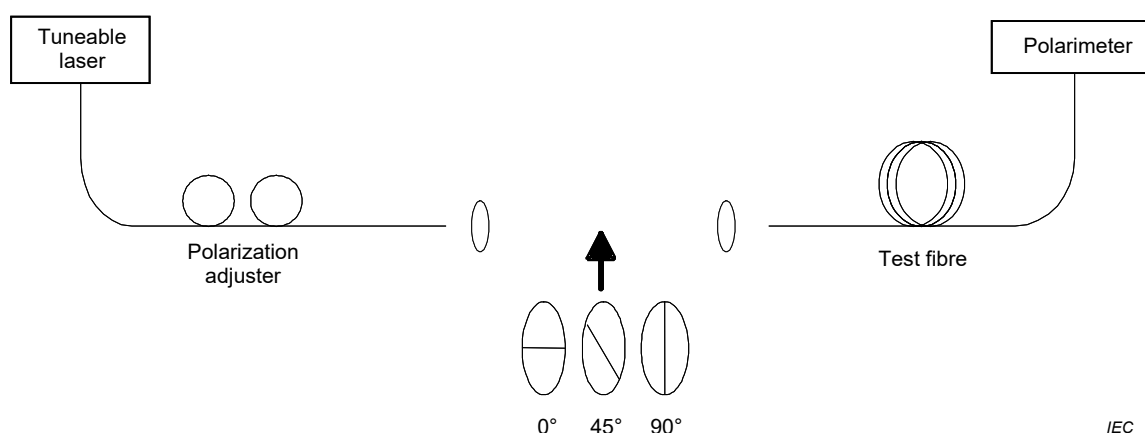


Figure B.1a – Narrowband source (JME)

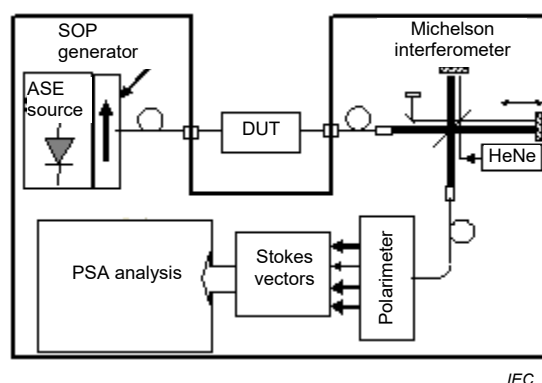


Figure B.1b – Broadband source (PSA)

Figure B.1 – Block diagram for method B

B.1.2 Light source

In all cases, two kinds of light sources may be used, depending on the type of polarimeter. A narrowband source such a tuneable laser shown in Figure B.1a can be used with a polarization analyser. Alternatively, a BBS shown in Figure B.1b can be used with a narrow bandpass filtering polarimeter such as an optical spectrum analyser or an interferometer used as a FT spectrum analyser placed before the polarimeter. In the case of BBS, the width of the filter is taken as the spectral width for the purpose of calculations.