

Optical fibres — Polarization mode dispersion measurement techniques for single-mode optical fibres

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National foreword

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CONTENTS

	Page
FOREWORD	4
Clause	
1 Scope and object	6
2 Symbols	8
3 Apparatus	10
3.1 Light source	10
3.2 Optical signal adjustments	10
3.2.1 Method A	10
3.2.2 Method B	11
3.2.3 Method C	11
3.3 Input optics (all methods)	11
3.3.1 Fibre pigtail	11
3.3.2 Optical lens system	12
3.3.3 Cladding mode stripper	12
3.4 Output optics	12
3.5 Signal detection	12
3.6 Computational equipment	12
3.7 Output signal polarization adjustments	12
4 Test sample	13
5 Procedure	13
5.1 Method A	13
5.2 Method B	14
5.3 Method C	15
5.3.1 Equipment calibration	15
5.3.2 Test procedure	15
6 Calculations	16
6.1 Method A	16
6.1.1 Cycle counting	16
6.1.2 Fourier analysis	17
6.1.3 Transform data fitting	17
6.1.4 Spectral range	19
6.2 Method B	19
6.2.1 Display of DGD versus wavelength	20
6.2.2 Average DGD	20
6.2.3 PMD coefficient	20
6.3 Method C	20
6.3.1 Weak mode coupling	20
6.3.2 Strong mode coupling	21
7 Results	21

Clause	Page
Annex A (informative) Determination of mode coupling regime	22
Annex B (informative) Strategies for improving precision	24
Annex C (informative) Peak identification algorithm for cycle counting for method A	26
Annex D (informative) Fourier analysis theoretical background for method A	28
Annex E (informative) Determination of PMD for method B (Jones matrix method)	31
Annex F (informative) Sample calculation for method B	34
Annex G (informative) PMD determination by method C for an interferogram with an autocorrelation peak	38
Annex H (informative) PMD intercomparison results and observations	40
Bibliography	43

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OPTICAL FIBRES –

Polarization mode dispersion measurement techniques for single-mode optical fibres

FOREWORD

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The text of this technical specification is based on the following documents:

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Full information on the voting for the approval of this technical specification 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 3.

Annexes A to H are for information only.

The committee has decided that this publication remains valid until _____.

At this date, in accordance with the committee's decision, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

OPTICAL FIBRES –

Polarization mode dispersion measurement techniques for single-mode optical fibres

1 Scope and object

This technical specification describes three test methods for measuring the polarization mode dispersion (PMD) of single-mode optical fibres of type B.

Method A: Fixed analyzer method

Method B: Jones matrix eigen-analysis/state of polarization method

Method C: Interferometric method

These methods can be applied to both short and long fibres in the limits of both zero and strong polarization mode coupling.

These methods are restricted to wavelengths greater than or equal to that at which the fibre is effectively single-mode. The cut-off wavelength of an uncabled fibre may be determined by method IEC 60793-1-C7A of IEC 60793-1-4, while the cut-off wavelength of a cabled fibre may be determined by method IEC 60793-1-C7B of IEC 60793-1-4.

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) time $\Delta\tau$ between pairs of orthogonally polarized principal states of polarization (PSP).

PSP are such that no pulse spreading due to PMD occurs when one (and only one) of the PSPs is excited. The maximum pulse spreading due to PMD occurs when both the PSPs are equally excited and is related to the difference in times of flight associated to the two PSPs. The PMD of a fibre is completely characterized by the DGD between the PSPs which varies randomly with optical frequency and time.

In long fibre spans, PMD is a random effect 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 $\langle\Delta\tau\rangle$ given by the RMS pulse broadening or the mean DGD between PSPs. 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 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 expected value $\langle\Delta\tau\rangle$. The DGD $\Delta\tau$ or pulse broadening $\delta\tau$ can be averaged over wavelength, yielding $\langle\Delta\tau\rangle_\lambda$, 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 $\langle\Delta\tau\rangle$.

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

$$\text{"short-length" PMD coefficient} = \langle \Delta\tau \rangle / L. \quad (1)$$

Fibres in practical systems are nearly always in the $L \gg l_c$ regime and mode coupling is strong. If mode coupling is also found to be random, $\langle \Delta\tau \rangle$ scales with the square root of fibre length, and

$$\text{"long-length" PMD coefficient} = \langle \Delta\tau \rangle / \sqrt{L} \quad (2)$$

The text provides means for deciding when it is appropriate to use equations (1) or (2) to calculate the PMD coefficient. Typical units are ps for $\Delta\tau$, km for L , ps/km for short-length PMD, and ps/ $\sqrt{\text{km}}$ for long-length PMD. See annex A for more detail on determining the mode coupling regime.

These methods can measure PMD on lengths of fibre limited only by the equipment resolution or dynamic range. In general, performing these measurements on lengths of fibre ≥ 1 km is recommended to characterize a fibre's performance in a long haul network. Sample lengths in the transition region $L \sim l_c$ may require additional analysis methods beyond the scope of those prescribed here.

For method A, calculations may be made in the frequency domain (cycle counting) or time domain (Fourier analysis). When cycle counting is used, $\langle \Delta\tau \rangle$ is the average over the measurement wavelength range, as shown in equation (10). In the $L \ll l_c$ limit, $\langle \Delta\tau \rangle = \Delta\tau$, i.e. the PMD equals the DGD. When Fourier analysis is used, and in the limit of $L \ll l_c$, $\langle \Delta\tau \rangle$ is obtained simply from the centroid value of the $\delta\tau$ values obtained over the measurement wavelength range. For the $L \gg l_c$ limit, $\langle \Delta\tau \rangle$ is determined from the second moment of the distribution $P(\delta\tau)$ of $\delta\tau$ values obtained over the measurement wavelength range.

Method B measures DGD $\Delta\tau$ as a function of wavelength, and PMD is expressed as $\langle \Delta\tau \rangle_\lambda$. DGD(λ) can be measured by using a Jones matrix determination (eigen-analysis) (JME) by examining the variation of the State of Polarization (SOP) with specific polarization state inputs over a range of input light wavelengths. In the SOP method, DGD is measured by analyzing the evolution of the SOP of the light exciting the fibre under test when the wavelength of the launched light is varied for constant SOP. In this case, when the optical frequency of the launched light is varied, the polarization states at the output of the fibre, represented on the Poincaré sphere, rotate around the axis coinciding with the direction of the PSPs at a rate dependent on the PMD delay: the greater the delay, the faster the rotation. Therefore, by measuring the rotation angle $\Delta\theta$ of the representative point on the Poincaré sphere corresponding to angular frequency variation $\Delta\omega$ the PMD delay $\Delta\tau$ is obtained as:

$$\Delta\tau = |\Delta\theta / \Delta\omega| \quad (3)$$

Method C determines PMD from the autocorrelation or crosscorrelation function of the emerging electromagnetic field at one fibre end when illuminated by a broadband source at the other end. In the case of the autocorrelation type instrument, the interferogram has a central coherence peak corresponding to the autocorrelation of the optical source.

2 Symbols

$:=$	is set to, for example $n := 1$ means “variable n is set to a value of 1”.
a	threshold level for chi squared test
A	multiplier for probability function
A_{median}	median value of A
$a_j^{(m)}$	polynomial fit coefficient
b_j	polynomial fit coefficient
c_0	velocity of light in vacuum
c_1	polynomial fit coefficient
d_i	polynomial fit coefficient
D	root mean square error
e	counter used in sec. 6.2.4.
E	number of extrema (maxima plus minima) in $R(\lambda)$
F	frequency of cosine wave $R'(\lambda)$
f_i	i th measured value of $R(\lambda)$
g	spike number
h	wavelength spacing between points
i	counter used in annex C
j	counter used in calculation and annex C
K	counter used in annex C
k	mode coupling factor
L	length of fibre/fibre cable test sample
L_c	source coherence length
l_c	mode coupling length
m	number of measured values used in polynomial fit
M'	number of data points in Fourier transform data above a threshold level T_2 within a spike, g
M''	number of significant data points in Fourier transform data above threshold level T_1 for strongly coupled case
n	number of discrete weakly coupled devices under test
N	number of times the fibre is measured
$P_A(\lambda)$	optical power recorded with analyzer in place
$P_{\text{ROT}}(\lambda)$	optical power recorded with analyzer rotated 90°
$P_{\text{TOT}}(\lambda)$	optical power recorded with analyzer removed
$P(\delta\tau)$	probability function of Fourier transform data
$P'(\delta\tau)$	predicted value of probability function of Fourier transform data

$R'(\lambda)$	ratio data (theory) for simple birefringent fibre
$R(\lambda)$	output ratio from PMD measurement system
T_1	first threshold level for $P(\delta\tau)$ data
T_2	second threshold level for $P(\delta\tau)$ data
t_c	optical source coherence time (method C)
X	criterion for number of valid points of $P(\delta\tau)$ below T_1
Δf	frequency variation in method B
$\delta\tau$	relative pulse delay arrival time
$\delta\tau_{\text{last}}$	$\delta\tau$ value at the last significant point of P , defined as the first P point that is above T_1 , but which is also followed by three or more points falling below T_1 . $\delta\tau_{\text{last}} = \delta\tau_M$.
$\delta\tau_{\text{max}}$	maximum $\delta\tau$ value that can be measured
$\delta\tau_{\text{min}}$	minimum $\delta\tau$ value that can be measured
Δn	fibre modal birefringence per unit length
$\Delta\tau$	differential group delay value
$\langle\Delta\tau\rangle$	average expected PMD over wavelength scan range
$\delta\lambda$	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
$\Delta\omega$	angular frequency variation in method B
λ	test wavelength used to measure PMD
λ_0	central wavelength of the light source
λ_1	first wavelength in set of test wavelengths (or position of first maximum or minimum in $R(\lambda)$)
λ_2	last wavelength in set of test wavelengths (or position of last maximum or minimum in $R(\lambda)$)
λ_{CC}	cut off wavelength of fibre cable under test
λ_{CF}	cut off wavelength of fibre under test
σ_R	second moment of Fourier transform data
ν	optical light frequency
X^2	chi squared variable
$\gamma_j^{(m)}$	coefficient defined by equation (C.4)

3 Apparatus

Schematic diagrams for typical equipment arrangements for methods A, B and C are shown in figures 1 to 3 respectively.

3.1 Light source

For method A, a light source is used which emits radiation at the intended measurement wavelengths, such as a broadband lamp, light emitting diode(s), or tunable laser(s). It shall be stable in intensity and spectral distribution over a time period long enough to perform the measurement.

For method B, a single-line laser or narrow band source is used which is tunable across the intended measurement wavelength range. The spectral distribution shall be narrow enough so that light emerging from the test fibre remains polarized under all conditions of the measurement. A degree of polarization (DOP) of 90 % or greater is preferred, although measurements may be performed with values as low as 25 % with reduced precision. For a given value of DGD $\Delta\tau$, the lowest degree of polarization which can result is given by

$$\text{DOP } 100 \% \times e^{-\frac{1}{4\ln(2)} \left(\frac{\pi c_0 \Delta\tau \Delta\lambda}{\lambda_0^2} \right)^2} \quad (4)$$

assuming a Gaussian spectrum of width $\Delta\lambda$ (Full Width-Half Maximum, FWHM) centred at λ_0 (c_0 is the velocity of light in free space). DOP is expressed in percent.

For method C, a broadband light source is used that emits radiation at the intended measurement wavelengths, such as a light emitting diode or a superfluorescent source. The central wavelength λ_0 shall be within the 1 310 nm or 1 550 nm window. The spectral shape shall be approximately Gaussian, without ripples that could influence the autocorrelation function of the emerging light. The spectral source line width must be known to calculate coherence time t_c .

The coherence time t_c is determined from the equation

$$t_c = \frac{\lambda_0^2}{\Delta\lambda \times c} \quad (5)$$

where

λ_0 is the central wavelength of the source;

$\Delta\lambda$ is the FWHM of the source;

c is the velocity of light in free space.

3.2 Optical signal adjustments

3.2.1 Method A

3.2.1.1 Monochromator

For method A, a specified set of test wavelengths is obtained by filtering the light source with a monochromator as in figure 1a, or by using an optical spectrum analyzer as the detector, as in figure 1b. This filtering is not needed when the source is a tunable laser (see figure 1c). The spectral distribution must be narrow enough to avoid major depolarization of the signal under the influence of the PMD of the fibre under test (see clause 6 for calculations). A polarizer at the fibre input is needed only if the launch beam is not already polarized (usually a 3 dB extinction ratio is sufficient).

3.2.2 Method B

3.2.2.1 Polarization adjuster

For the JME method a polarization adjuster follows the laser and is set to provide roughly circularly polarized light to the polarizers, so that the polarizers never cross polarization with their input light. The polarization is adjusted as follows. The tunable laser wavelength is set to the centre of the range to be measured. Each of the three polarizers is inserted into the beam, and three corresponding power measurements are performed at the output of the polarizers. The source polarization is adjusted via the polarization adjuster such that the three powers fall within approximately a 3 dB range of one another. In an open beam version of the set-up, a waveplate may perform the polarization adjustment.

For the SOP method, the polarization controller is set so as to optimize the conditions for the determination of the rotation angle on the Poincaré sphere, if necessary.

3.2.2.2 Polarizers

For the JME method, three linear polarizers at relative angles of approximately 45° are arranged to be inserted into the light beam in turn. The actual relative angles shall be known. For the SOP method a polarization controller is placed between the optical source and the fibre under test.

3.2.3 Method C

3.2.3.1 Polarizer

The polarizer shall polarize over the full wavelength range of the source. The polarizer extinction ratio over the source spectral range should be >20 dB.

3.2.3.2 Beam splitter

The beam splitter of the interferometer is used to split the incident polarized light into two components propagating in the interferometer's arms. The splitter can be an optical fibre coupler or a cube beam splitter.

3.2.3.3 Interferometer

The interferometer can be an air path type or a fibre type. It can be of Michelson or Mach-Zehnder type, and it can be located at the source or at the detector end of the device under test. A quarter wave plate, for example, can be used to remove the autocorrelation peak response of the interferometer.

3.3 Input optics (all methods)

An optical lens system or single-mode fibre pigtail may be employed to excite the test fibre. The power coupled into the fibre shall be stable for the duration of the test.

3.3.1 Fibre pigtail

If pigtails are used, interference effects due to reflections should be avoided. This may require index matching materials or angled cleaves. The pigtails shall be single-mode.

3.3.2 Optical lens system

If an optical lens system is used, some suitable means, such as a vacuum chuck, shall be used to stably support the input end of the fibre.

3.3.3 Cladding mode stripper

Any cladding mode power should be removed from the test fibre. Under most circumstances, the fibre coating will perform this function; otherwise, employ a device that extracts cladding mode power.

3.4 Output optics

The power emitted from the test fibre must be coupled onto the active region of the detection system (see figures 1 to 3). An optical lens system, a butt splice to a single-mode fibre pigtail, or an index-matched fibre-to-fibre coupling made directly to the detection system are examples of means that may be used.

3.5 Signal detection

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, optical spectrum analyzer, or a polarimeter. To use the entire spectral range of the source, the detection system must have a wavelength range which includes the wavelengths produced by the light source.

3.6 Computational equipment

A digital computer may be used for purposes of equipment control, data acquisition and/or numerical evaluation of the data.

3.7 Output signal polarization adjustments

Method A – Polarizer and analyzer

The angular orientation of the polarizers is not critical, but should remain fixed throughout the measurement. With weak mode coupling, some adjustment of the polarizer orientation may be helpful in maximizing the amplitude of the oscillations in figure 4. Alternatively, this may be achieved by rotation of the fibre(s) at splices or connectors.

The analyzer is not needed when a polarimeter is used for signal detection.

Method B – Polarimeter

For the Jones matrix method, a polarimeter is used to measure (as a function of wavelength) the three output states of polarization corresponding to insertion of each of the three polarizers. For the SOP method, a polarimeter is used to measure the Stokes parameters as a function of wavelength. For both methods, the wavelength range of the polarimeter shall include the wavelengths produced by the light source.