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Second edition
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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 du mode de polarisation

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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 second edition cancels and replaces the first edition published in 2003. It constitutes a technical revision. In this edition, reference to IEC 61282-9 has resulted in the removal of Annexes E, F, G and H as well as the creation of a new Annex E.

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

CDV	Report on voting
86A/1038/CDV	86A/1078/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 standard is to be read in conjunction with IEC 60793-1-1.

A list of all parts of 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 maintenance result 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

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- withdrawn;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

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 the expected value, $<\Delta\tau>$, or the mean DGD over wavelength. In principle, the expected value $<\Delta\tau>$ 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, $<\Delta\tau>$ 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 $<\Delta\tau>$. The DGD $\Delta\tau$ or pulse broadening $\delta\tau$ can be averaged over wavelength, yielding $<\Delta\tau>_\lambda$, or time, yielding $<\Delta\tau>_t$, or temperature, yielding $<\Delta\tau>_T$. For most purposes, it is not necessary to distinguish between these various options for obtaining $<\Delta\tau>$.

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 $L << l_c$, mode coupling is negligible and $<\Delta\tau>$ scales with fibre length. The corresponding PMD coefficient is

$$\text{"short-length" PMD coefficient} = <\Delta\tau>/L.$$

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

$$\text{"long-length" PMD coefficient} = <\Delta\tau>/\sqrt{L}$$

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 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 60793-1-1, *Optical fibres – Part 1-1: Measurement methods and test procedures – General and guidance*

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

IEC 60793-2-50, *Optical fibres – Part 2-50: Product specifications – Sectional specification for class B single-mode fibres*

IEC 60794-3, *Optical fibre cables – Part 3: Sectional specification – Outdoor cables*

IEC 61280-4-4, *Fibre optic communication subsystem test procedures – Part 4-4: Cable plants and links – Polarization mode dispersion measurement for installed links*

IEC/TR 61282-3, *Fibre optic communication system design guides – Part 3: Calculation of link polarization mode dispersion*

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

IEC 61290-11-1, *Optical amplifier test methods – Part 11-1: Polarization mode dispersion – Jones matrix eigenanalysis method (JME)*

IEC 61290-11-2, *Optical amplifiers – Test methods – Part 11-2: Polarisation mode dispersion parameter – Poincaré sphere analysis method*

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

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

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 and definitions

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

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

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 analyzing the measured results are also provided.

– Method A
  - Fixed analyser (FA)
  - Extrema counting (EC)
  - Fourier transform (FT)
  - Cosine Fourier transform (CFT)
– Method B
  - Stokes parameter evaluation (SPE)
  - Jones matrix eigenanalysis (JME)
  - Poincaré sphere analysis (PSA)
  - State of polarization (SOP)
– Method C
  - Interferometry (INTY)
  - Traditional analysis (TINTY)
  - 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 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.

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

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

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

NOTE 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_{AVG} 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_{AVG}. If mode coupling is reduced, the resultant reported PMD value from these methods may exceed those that can be reported by the frequency domain measurements that report PMD_{AVG}, 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 $ps/km^{1/2}$. 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 (in an implementation capable of millisecond measurement time scales) is appropriate.

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.

– 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.

– 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.

– By taking the cosine Fourier transform of the difference of the normalized spectra from two orthogonal analyzer settings and calculating the RMS of the squared envelope. The PMD_{RMS} 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 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. 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:

$$\frac{\mathrm{d}s(\omega)}{\mathrm{d}\omega} = \Omega(\omega) \times s(\omega) \tag{4}$$

$$\Delta\tau(\omega) = |\Omega(\omega)| \tag{5}$$

where

s is the normalized output Stokes vector;

[1)] Figures in square brackets refer to the Bibliography.

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) must be launched for each wavelength.

The JME approach is completed by transforming the output Stokes vectors to Jones matrices [2], appropriate combination of the matrices at adjacent wavelengths, and 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 61282-9).

The SOP approach is based on a piecewise evaluation of Equation (4) using the normalized measured Stokes vectors. The SOP approach can yield good results when the transit of the output Stokes vector is well behaved (negligible mode-coupling) but can produce incorrect results when the output Stokes vector changes rapidly and randomly (see IEC 61282-9). The extra measurement time required for the three input SOPs for JME and PSA result in a more robust measurement.

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 61282-9), both of which measure the PMD_{RMS} value:

– TINTY uses a set of specific operating conditions for its successful applications and a basic setup;

– GINTY uses no limiting operating conditions but in addition to the same basic set-up also using a modified setup compared to TINTY.

With the exception of the Method B SOP approach, 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, e.g., 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 61282-9 provides the mathematical formulations for all methods.

4.2 Reference test method

Method B, SPE (only JME and PSA approaches), 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 externally induced mode-coupling is minimized. Sources of such external mode-coupling can be:

a) excessive tension;

b) excessive bending induced from
   - fibre cross-overs on a shipping reel;
   - crimping of fibre within a cable on a spool that is too small;
   - 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 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 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 61282-9.

5 Apparatus

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.

5.1 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 61282-9 provides additional guides concerning the source input SOP, degree of polarization (*DOP*), use of polarizers and polarization controllers.

5.2 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.

5.3 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.

5.4 Cladding mode stripper

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

5.5 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 = 30 mm on the fibre is generally sufficient.

5.6 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.

5.7 Output optics

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

5.8 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, optical spectrum analyser, 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. See Annex A, B, or C, as appropriate, for additional details.

5.9 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 must be fixed in position at a nominally constant temperature throughout the measurement. Standard ambient conditions 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