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Fibre optic communication system design guides –

Part 9: Guidance on polarization mode dispersion measurements and theory

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 9: Guidance on polarization mode dispersion measurements and theory

FOREWORD

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IEC 61282-9, which is a technical report, has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

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

Enquiry draft	Report on voting
86C/696/DTR	86C/703/RVC

Full information on the voting for the approval of this technical report 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.

A list of all parts of IEC 61282 series, published under the general title *Fibre optic communication system design guides,* 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- withdrawn,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.

A bilingual version of this publication may be issued at a later date.

FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 9: Guidance on polarization mode dispersion measurements and theory

1 Scope

This technical report applies to all commercially available fibre optic products sensitive to polarization mode dispersion (PMD).

This report presents general information about PMD, the mathematical formulation related to the application of the generally accepted methods to test PMD, and some considerations related to the sampling theory regarding the use of different light sources and detection systems.

This report is complementary to the International Standards describing the PMD procedures (IEC 60793-1-48, IEC 61280-4-4, IEC 61290-11-1, IEC 61290-11-2 and IEC 61300-3-32) and other design guides on PMD (IEC 61282-3 and IEC 61292-5).

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 60793-1-48: *Optical fibres – Part 1-48: Measurement methods and test procedures – Polarization mode dispersion*

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 61290-11-1: *Optical fibre 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: Polarization mode dispersion parameter – Poincaré sphere analysis method*

IEC 61300-3-2: *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 3-2: Examinations and measurements – Polarization dependence of attenuation in a single-mode fibre optic device*

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 for passive optical components* [1]

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

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

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[1] To be published

3 Acronyms and abbreviations

ASE	amplified spontaneous emission
AWG	array waveguide grating
BBS	broadband source
BER	bit error rate or bit error ratio
Clh	circular left handed
Crh	circular right handed
CSO	composite second-order beat noise
DAS	differential attenuation slope
DGD	differential group delay
DOP	degree of polarization
DUT	device under test
DVV	polarization dispersion vector velocity
DWDM	dense wavelength division multiplexing
EC	extrema counting
EDFA	erbium doped fibre amplifier
FA	fixed analyser
FAFT	fixed analyser Fourier transform
FAEC	fixed analyser extrema counting
FCFT	fast cosine Fourier transform
ffs	for further study
FT	Fourier transform
FWHM	full width at half the maximum
GINTY	general analysis for the interferometric method
HMD	harmonic distortion
IMD	intermodulation distortion
INTY	interferometry
I/O	input/output
ISI	inter-symbol interference
JME	Jones matrix eigenanalysis
L	linear
LH	linear horizontal
LV	linear vertical
MMA	Mueller matrix analysis
MPS	modulation phase shift
OA	optical amplifier
OFA	optical fibre amplifier
OSA	optical spectrum analyser
OTDR	optical time domain reflectometer
P-	parallel polarization (to the plane of incidence)
PDCD	polarization dependent chromatic dispersion
PDD	polarization dependent delay
PDG	polarization dependent gain

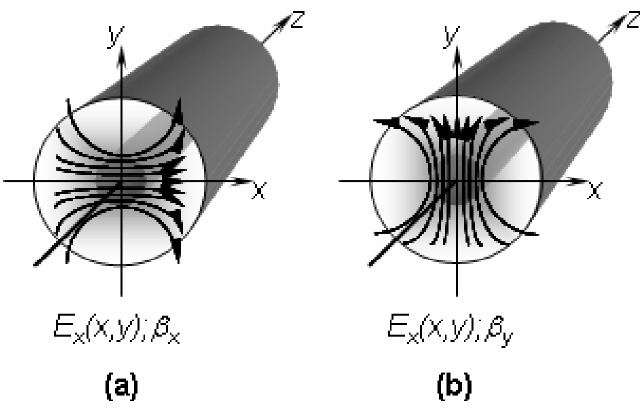
PDL	polarization dependent loss
PDV	polarization dispersion vector
PM	polarization mode
PMD	polarization mode dispersion
PMD_1	first-order polarization mode dispersion
PMD_2	second-order polarization mode dispersion
PMF	polarization maintaining fibre
POTDR	polarization optical time domain reflectometer
POWA	planar optical waveguide amplifier
PPS	polarization phase shift
PS	Poincaré sphere
PSA	Poincaré sphere analysis
PSP	principal states of polarization
RBW	resolution bandwidth
RMS	root mean square
RTM	reference test method
S	source
SMSR	side mode suppression ratio
SOP	state of polarization
SPE	Stokes parameter evaluation
SRM	standard reference material
SSE	source spontaneous emission
TINTY	traditional analysis for the interferometric method
TLS	tuneable laser source
TSSE	total source spontaneous emission
WDM	wavelength division multiplexing

4 General information

The following text provides general information concerning the PMD theory and phenomenon. In that context, the word “device” or “device under test” (DUT) is used throughout the text in the sense of an optical path with an input and an output interface, such as an optical fibre, an optical fibre cable, an optical component, an optical amplifier, etc. The device may be connectorised.

4.1 Polarization modes

The solution of the wave equation has degenerated eigenvalues. This means that even the fundamental solution is degenerated. A single-mode fibre can therefore support several modes, the polarization modes (PM), and by analogy can be considered as a multi-(polarization) mode fibre. In particular, the lowest order mode, namely the fundamental HE_{11} (LP_{01}) mode, can be chosen to have its transverse electric field predominately along the x-direction; the orthogonal polarization is an independent mode, as shown in Figure 1.



IEC 1246/06

Figure 1 – Two electric field vector polarizations of the HE$_{11}$ mode in an optical fibre along the a) x-direction and b) y-direction

In a lossless optical fibre, the electric field vector of a monochromatic electromagnetic wave propagating along the z-direction can be described by a linear superposition of these two PM in the x-y transverse plane as shown in Equation (1) and in Figure 1 [1,2][2].

$$E = \{[A_x(z) \cdot E_x(x,y)] + [A_y(z)) \cdot E_y(x,y)]\} \cdot e^{-i\omega t} \qquad (1)$$

where

$A_x(z)$ $= E_x e^{i\beta_x z}$, is the complex coefficient describing the amplitude E_x and the phase β_x of the PM along the x-direction propagating in the z-direction;

$A_y(z)$ $= E_y e^{i\beta_y z}$, is the complex coefficient describing the amplitude E_y and the phase β_y of the PM along the y-direction propagating in the z-direction;

$E_x(x,y)$ is the spatial variation (in the x-y transverse plane) of the electric field vector of the PM along the x-direction (see Figure 1(a);

$E_y(x,y)$ is the spatial variation (in the x-y transverse plane) of the electric field vector of the PM along the y-direction (see Figure 1(b);

β_x $= kn_x$, is the propagation constant (also called effective index or wavenumber) of the PM along the x-direction with the index of refraction n_x; β_x, through n_x has a dependence on optical angular frequency ω, or optical frequency ν, or wavelength λ;

β_y $= kn_y$, is the propagation constant (also called effective index or wavenumber) of the PM along the y-direction with the index of refraction n_y; β_y, through n_y has a dependence on angular optical frequency ω, or optical frequency ν, or wavelength λ;

k $= 2\pi\nu = 2\pi/\lambda = \omega/c$, is the propagation constant with the wavelength λ in vacuum;

ν is the optical frequency in s^{-1} or Hz;

ω is the angular optical frequency in rad/s;

c is the speed of light in vacuum;

z is the distance in the device along the optical axis; $z = L$ at the output of the device with length L.

The complex ratio $A_x(z)/A_y(z)$ describes the state of polarization (SOP) defined in the x-y plane of the wave propagating along the z-direction.

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[2] Figures in square brackets refer to the Bibliography.

In an ideal optical fibre with perfect circular symmetry,

- $\beta_y = \beta_x$;
- the two PM are degenerate;
- consequently, any wave with a defined input SOP will propagate unchanged along the z-direction throughout the output of the fibre.

However, in a practical optical fibre, imperfections produced by the fabrication process, cabling, field installation/use or the environment break the circular symmetry,

- $\beta_y \neq \beta_x$, implying a phase difference, and index of refraction difference Δn and a phase velocity difference Δv between the two PM;
- the degeneracy of the two PM is lifted;
- consequently, the SOP of an input wave will change along the z-direction throughout the output of the fibre.

The difference between β_y and β_x, namely $\Delta\beta$, is called the phase birefringence or simply the birefringence and has units of inverse length. Birefringence may also be referred to as the index difference, Δn. Index differences typically vary between 10^{-7} and 10^{-5} in commonly available single-mode fibres [2].

4.2 Birefringence

Birefringence is produced by an anisotropic distribution of the index of refraction in the propagating region of an optical device medium. As such, any device is susceptible to birefringence. For instance, birefringence is produced by asymmetry in the optical fibre core, meaning when the circular symmetry of the fibre core is broken [1,3].

It is well known that the asymmetry provides an index of refraction that is smaller along an axis, and as such that smaller index provides a faster phase velocity along that axis compared to the other one. That axis is consequently called the fast axis as opposed to the other one, which is called the slow axis, corresponding to a larger index and a slower phase velocity. The slower wave is also said to be retarded compared to the other one.

The asymmetry can result from geometrical deformation of the medium or material anisotropy through various elasto-optic, magneto-optic or electro-optic changes of the index of refraction. Geometrical deformation and asymmetric lateral stress via elasto-optic index changes may be produced during fabrication, for instance, and will typically produce linear birefringence. Bending, kinks and electro-optic Kerr effect will also typically produce linear birefringence. Twist and magneto-optic effect via Faraday effect will produce circular birefringence.

Several of these mechanisms may coexist and may be present in various numbers, strengths and distributions; and may vary with time and over environmental conditions. This makes the SOP along the propagating medium and at the output unpredictable and unstable and, consequently, PMD compensation difficult to achieve.

Birefringence can, however, be imposed, such as is the case for polarization maintaining fibre (PMF). This type of fibre has a strong birefringence maintained along the fibre length which can be created, for example, by introducing stress in one plane. This will keep the two PM non-degenerate. Any SOP launched aligned with the axis of one of these two PM will be maintained throughout the fibre. As opposed to PMF, commonly available single-mode fibres used for fibre optic transmissions in the field are weakly birefringent fibres.

4.3 Beat length

Birefringence makes the two PM slip in phase relative to one another as they propagate at different phase velocities. When the phase difference between the two PM is equal to an integer number of 2π, the two PM beat with one another, and at that periodic point along the z-direction, the input SOP is reproduced. The length corresponding to that periodicity is called the beat length L_b.

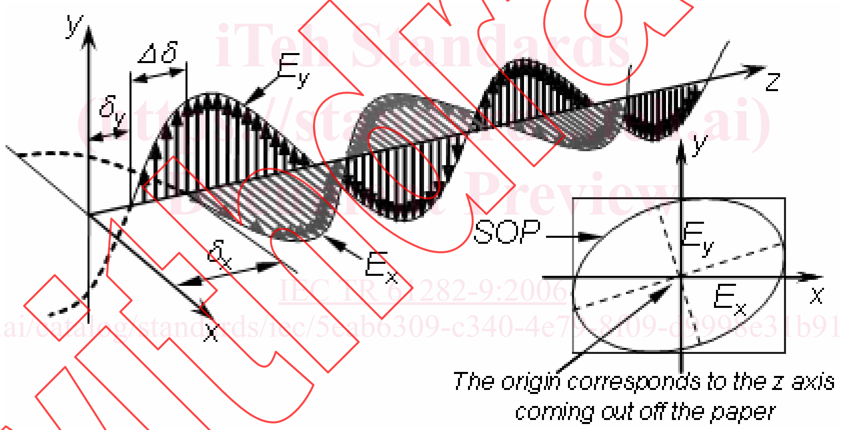
$$L_b = \frac{2\pi}{\Delta\beta} \quad \text{in units of length} \tag{2}$$

Beat lengths typically vary between 2 m and15 m in commonly available single-mode fibres [2].

Beat length should not be confused with coupling length, which will be explained later.

4.4 Polarization transfer function

Polarized light and its related SOP can be represented using Jones calculus [4] as a complex vector illustrating the x- and y- components of the electric field of the SOP at a point in space (see Figure 2).



IEC 1247/06

Figure 2 – Cartesian and elliptical representation of a state of polarization

NOTE In the presence of anisotropy, the y axis is the slow axis in Figure 2, while the x axis is the fast axis, and the wave propagating in the y-z plane is retarded. The resulting wave from the vector combination of the y-z plane wave and the x-z plane wave is shown in the x-y plane in the lower right corner of Figure 2

The Jones vector has the form (not considering any unit vector):

$$E = \begin{pmatrix} A_x \\ A_y \end{pmatrix} = \begin{pmatrix} E_x e^{i\delta_x} \\ E_y e^{i\delta_y} \end{pmatrix} \tag{3}$$

Equation (3) can easily be related to Equation (1) in case of anisotropy when δ becomes β. As polarized light traverses any DUT such as an optical fibre, its SOP undergoes a transformation. This transformation is described in Jones calculus by the complex 2x2 Jones matrix, T, so that the output Jones vector E_{out} is related to the input Jones vector E_{in} through $E_{\text{out}} = \text{T}\ E_{\text{in}}$. The Jones matrix is determined by measuring the output Jones vectors in response to any three unique input vectors. The calculation is simplest when the stimuli are linear horizontal (LH) 0 ° ($E_y = 0$; $\delta_x = 0$), linear vertical (LV) 90 ° ($E_x = 0$, $\delta_y = 0$) and linear (L) +45 ° ($E_y = E_x$; $\delta_y = \delta_x = 0$) SOPs. If the responses to the three stimuli are: