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TECHNICAL REPORT

colour
inside

Fibre optic communication system design guides –
Part 13: Guidance on in-service PMD and CD characterization of fibre optic links

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

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FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 13: Guidance on in-service PMD and CD characterization of fibre optic links

FOREWORD

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IEC TR 61282-13, 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/1201/DTR	86C/1236/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 in the IEC 61280 series, published under the general title *Fibre-optic communication subsystem test procedures*, 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

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- withdrawn,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

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

INTRODUCTION

The International Electrotechnical Commission (IEC) draws attention to the fact that it is claimed that compliance with this document may involve the use of a patent concerning optical frequency-sensitive analyser given in 5.1.3.4 and concerning CD measurement using multi-tone probe signal given in 6.1.

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FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 13: Guidance on in-service PMD and CD characterization of fibre optic links

1 Scope

This part of IEC 61282, which is a technical report, presents general information about in-service measurements of polarization mode dispersion (PMD) and chromatic dispersion (CD) in fibre optic links. It describes the background and need for these measurements, the various methods and techniques developed thus far, and their possible implementations for practical applications.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60793-1-42, *Optical fibres – Part 1-42: Measurement methods and test procedures – Chromatic 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*

3 Symbols, acronyms and abbreviated terms

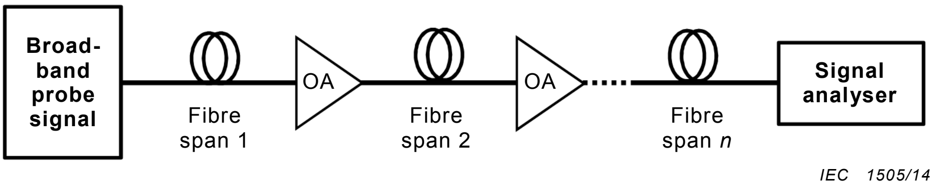
$D(\lambda)$	group velocity dispersion coefficient at optical wavelength λ
F	frequency of amplitude modulation in CD measurement
L	length of arc of the SOP rotation on the Poincaré sphere
L_f	length of fibre or fibre link
P_p, P_s	optical signal powers in two orthogonal SOPs
$\overset{\frown}{P}$	normalized optical power
$\Delta\overset{\frown}{P}$	normalized optical power difference
S_1 , S_2 , S_3	Stokes parameter
$\hat{S}$	normalized Stokes vector
N	number of statistically independent effective DGD measurements
N_t	number of statistically independent effective DGD measurements in time
N_v	number of statistically independent signal wavelengths
c	speed of light in vacuum
Δf	optical frequency interval or spacing
f	electrical signal frequency in dual-wavelength frequency generator
f_clock	clock frequency of digital data modulation
Δt	time interval between effective DGD measurements or differential time delay in CD measurement

Δt_{corr}	correlation time of effective DGD variations
$\Delta\phi$	differential phase shift in CD measurement
$\delta\lambda$	wavelength increment (interval, spacing or step size)
$\delta\nu$	optical frequency increment (interval, spacing or step size)
$\Delta\lambda$	optical source spectral width or linewidth (FWHM unless noted otherwise)
$\Delta\nu$	optical frequency interval or spacing
$\Delta\tau$	differential group delay value
$\Delta\tau_{eff}$	effective or partial DGD value, $\Delta\tau_{eff} = \Delta\tau \sin\varphi$, where φ is the angle between PSP vector and signal SOP vector on the Poincaré sphere
$<\Delta\tau>$	average DGD over a wavelength range or time interval
$<\Delta\tau_{eff}>$	average effective DGD over a wavelength range or time interval
$<\Delta\tau^2>^{1/2}$	average RMS DGD over a wavelength range or time interval
λ	optical wavelength
ν	optical light frequency
φ	angle between PSP and signal SOP vector on the Poincaré sphere
$\Phi(\nu)$	optical phase shift introduced by GVD in the spectral components of a modulated signal
ψ	angle between two Stokes vectors
σ	standard deviation of DGD measurements
θ	polarization rotation angle on the Poincaré sphere
ACF	autocorrelation function
ADC	analogue-to-digital converter
AM	amplitude modulation
ASE	amplified stimulated emission (from optical amplifiers)
BPF	optical or electrical band-pass filter
CD	chromatic dispersion
CW	continuous wave
DGD	differential group delay
DMUX	wavelength division de-multiplexer
DOP	degree of polarization
DPSK	differential phase shift keying
DSP	digital signal processing or processor
GVD	group velocity dispersion
JME	Jones matrix eigenanalysis (PMD test method)
LO	local oscillator or local oscillator laser
MT	monitoring port or tap
MUX	wavelength division multiplexer
NRZ	non-return-to-zero modulation
OA	optical amplifier
OOK	on-off keying
OTDR	optical time-domain reflectometry
PDF	probability density function

PC	variable polarization controller
PBS	polarization beam splitter
PD	photo detector
PM	phase modulation
PMD	polarization mode dispersion
PSK	phase shift keying
PSP	principal SOP
QPSK	quadrature phase shift keying
ROADM	reconfigurable optical add-drop multiplexer
RF	radio frequency
RZ	return-to-zero modulation
SOP	state of polarization
WDM	wavelength division multiplexing or multiplexer

4 Background

Excessive chromatic or polarization mode dispersion in fibre optic links may severely impair the transmission of high-speed optical signals. It is therefore important to accurately characterize the end-to-end optical properties of a fibre link before it is put into service. CD or PMD in a fibre link may be characterized using any of the measurement methods described in international standards, such as IEC 60793-1-42 for CD measurements and IEC 61280-4-4 for PMD measurements. A common feature of these methods is that they require either broadband or broadly tuneable optical probe signals to be injected into one end of the link while the optical properties of the fibre are analysed at the other end (see Figure 1). Consequently, the fibre link cannot carry any traffic during the duration of the measurement and has to be taken out of service.



Key

OA	optical amplifier

Figure 1 – Out-of-service fibre characterization with broadband optical probe signal

Such out-of-service measurements are usually acceptable when a new fibre link is installed. However, they are highly undesirable when the fibre dispersion needs to be re-measured in a link that already carries commercial traffic [1][1]. This situation may occur, for example, when a link is considered to be upgraded to a higher bit rate, e.g. from transmitting 10-Gb/s NRZ-OOK to 40-Gb/s DPSK signals, or during occasional troubleshooting. When conventional fibre characterization methods are used, all signals carried by the link have to be re-routed to other links before the measurement can be performed.

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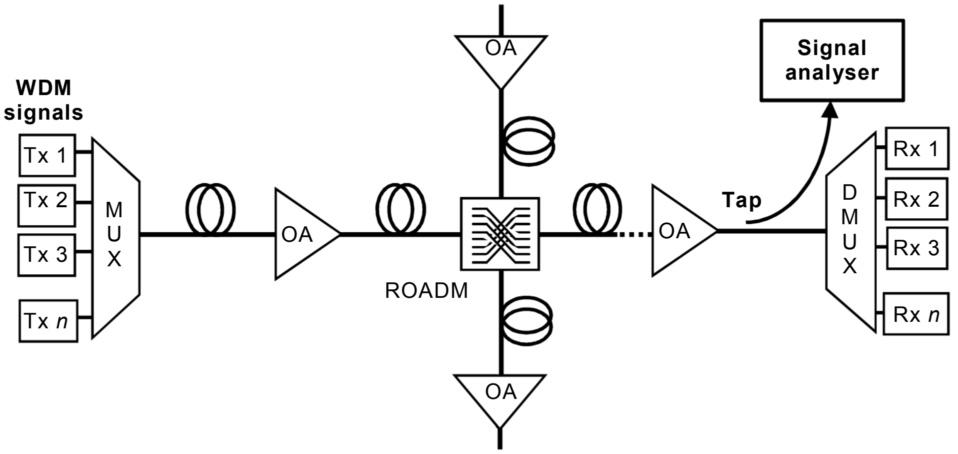
[1] Numbers in square brackets refer to the Bibliography.

To avoid such time-consuming re-configuration of network traffic, various methods have been developed for measuring fibre properties in transmission links that carry live commercial traffic [2-11]. An important requirement for in-service fibre characterization is that the measurement procedure must at any time interrupt or otherwise impair the transmission of traffic signals through the fibre.

This technical report describes the measurement principle and application of seven different in-service fibre characterization methods as well as their impact on network operation.

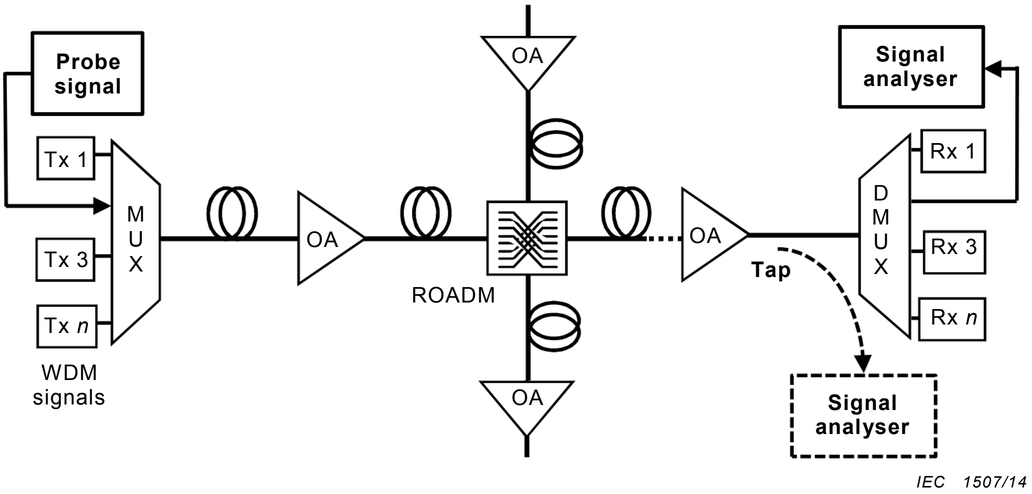


IEC 1506/14

Key

Tx	optical transmitter
Rx	optical receiver
OA	optical amplifier
MUX	WDM multiplexer
DMUX	WDM demultiplexer
ROADM	reconfigurable optical add-drop multiplexer

Figure 2 – In-service fibre characterization with non-intrusive method



Key

Tx	optical transmitter
Rx	optical receiver
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Figure 3 – Semi-intrusive in-service fibre characterization using narrowband probe signal

In-service fibre characterization methods may be divided into three categories:

a) Completely non-intrusive methods which measure the desired fibre property by analysing the transmitted traffic signals at pre-installed monitoring ports (or taps) along the link, as shown in Figure 2. These methods do not interfere with the normal operation of the fibre link (just like in-service OSNR measurement techniques). Some of these methods employ high-speed optical receivers which recover or analyse the transmitted data [2-6], whereas others only analyse the spectral or polarization characteristics of the transmitted signal [7]. Non-intrusive methods have been employed to measure end-to-end CD and PMD.

b) Semi-intrusive methods which employ special optically narrow-band probe signals to measure the desired fibre property [8-12]. These probe signals are usually injected into unused (i.e. empty) WDM channels at the input of the link, via a pre-installed WDM multiplexer, and co-transmitted with the normal traffic signals, as shown in Figure 3. Methods using probe signals are generally considered to be intrusive, even though the measurement may not interrupt transmission of the traffic signals, because modern networks often require provisioning of the transport system to allow alien signals to pass through optical amplifiers and ROADM nodes. In addition, the co-transmission of probe signals may adversely affect the quality of the traffic signals through nonlinear interactions in the fibre (such as four-wave mixing or cross-phase modulation). Probe signals are often employed to measure end-to-end CD and PMD in fibre links and can be designed to be particularly sensitive to the fibre property to be measured [8, 10, 12]. However, the signals must meet the required optical power levels and/or spectral shape expected by optical channel monitors in ROADM nodes, as they otherwise may be blocked [1].

c) Out-of-band measurement methods using probe signals at optical frequencies that are outside of the band used for transmission of traffic signals. Pre-installed WDM couplers are required to inject and extract the probe signals without traffic interruption. Usually, out-of-band signals do not pass through optical amplifiers and/or ROADM nodes along the link. This method is predominantly used for in-service OTDR measurements to monitor fibre and connector losses during operation.

The non-intrusive fibre characterization methods of category a) avoid any interference with the network operation and, hence, may be performed at any time and over any desired length of time. This aspect is important if the fibre property to be measured fluctuates with time, like in the case of PMD, and needs to be monitored over a longer period of time [13]. Furthermore, all non-intrusive methods are single-ended measurements and, hence, require test equipment only at the receiving end of the fibre link, whereas the semi-intrusive methods of category b) need an additional probe signal generator at the input of the fibre link.

5 Non-intrusive fibre characterization

5.1 PMD measurement via polarization-sensitive spectral analysis

5.1.1 Introductory remark

This clause describes a truly non-intrusive method and apparatus for in-service PMD measurements on fibre links carrying conventional single-polarized WDM signals, i.e. signals that are transmitted in a single state of polarization (SOP). Just like many other out-of-service or intrusive PMD measurement methods, this method assumes that the PMD in the fibre link is composed of a large number of birefringent sections, which are randomly oriented and randomly distributed along the fibre link, so that the instantaneous DGD, measured at different optical frequencies and/or different times, is randomly distributed with a Maxwellian probability density function (PDF) [14].

It should be noted that the assumption of a Maxwellian PDF for the statistical distribution of the DGD is widely used to assess the PMD-induced transmission impairments of a fibre link. In fact, the main reason for measuring the mean DGD in fibre links is to estimate the probability of PMD-induced transmission outages, which can occur when the randomly varying DGD exceeds a certain maximal value, beyond which the transmitted signals may become severely distorted, so that they cannot be received without errors [14].

The likelihood of transmission outages in a fibre link can be determined from the measured value of the mean DGD only if the statistical distribution of the DGD is known. This distribution is normally assumed to have a Maxwellian PDF, and this assumption has been preponderantly confirmed in numerous investigations of medium- and long-distance fibre links. Therefore, the assumption of a Maxwellian-distributed DGD in the method described below does not restrict its applicability for measuring the mean DGD in fibre links to assess the likelihood of PMD-induced transmission outages.

The method employs a combined optical spectrum and polarization analyser, i.e. a spectrally narrowband polarimeter whose centre frequency can be tuned continuously over a sufficiently large range. This analyser is connected to a broadband monitoring port at the end of a fibre link and measures the optical frequency dependence of the polarization state in each transmitted optical signal. The optical resolution bandwidth of this analyser has to be substantially smaller than the spectral bandwidth of each data-carrying signal transmitted over the fibre link. This polarization-sensitive spectral analysis may be performed on any single-polarized signal, having arbitrary launch SOP, and does not require knowledge of the particular modulation format or symbol rate of the transmitted signals. Thus, it may be readily applied in mixed transmission systems carrying signals of different symbol rates and/or modulation formats.

The polarization analysis shall be performed – either simultaneously or consecutively – on all WDM signals that traverse the fibre link under test, but shall not include polarization-multiplexed signals or signals that have traversed other fibre links prior to entering the selected link. From this set of measurements one can then estimate the mean DGD in the fibre link, as explained in more detail in 5.1.2. Just like for conventional PMD measurements, the uncertainty of this estimate depends on the frequency range covered by the analysed WDM signals, as well as on the number of WDM signals included in the set of measurements. In general, the uncertainty is smallest when the WDM signals are equidistantly distributed over the largest possible frequency range (see 5.1.4 for more details).

The uncertainty of the estimated mean DGD may be reduced further by repeating the polarization analysis on the transmitted WDM signals periodically over a sufficiently long time interval. The mean DGD in the fibre link is then determined from the time- and frequency-average of the measured frequency dependence of the polarization state variations in the individual signal spectra. In the extreme case, the mean DGD in a fibre link may be assessed from a set of periodically repeated polarization analyses on just one selected WDM signal. The uncertainty of the mean DGD derived from these single-signal measurements depends on the total measurement time and may be estimated from the speed and magnitude of the DGD fluctuations observed in the measurements (see 5.1.4).

Therefore, this method may be applied to directly measure the end-to-end PMD of individual signal paths in ROADM networks, wherein the various WDM signals may traverse different fibre spans, because they are added (and dropped) at different locations. As a result, one may find fibre links where only a small number of the received signals have traversed the exact same signal path. Only these signals should be included in the polarization analysis and used to calculate the mean DGD. Because the uncertainty of a PMD measurement generally increases inversely with the number of analysed signals, it is important to include all signals in the analysis that have traversed the same signal path. The benefits of using more signals is limited by their correlations, as explained in more detail in 5.1.4.

End-to-end PMD measurements of signal paths generally avoid errors associated with the concatenation of span-by-span PMD characterization. Furthermore, because the PMD analysis may be performed at other points along the fibre link where a monitoring tap is installed, it may thus be possible to identify fibre sections with particularly high PMD values. In either case, performing these in-service PMD measurements has absolutely no impact on the operation of the network. The accuracy of the method has been asserted in lab experiments as well as in field trials and found to be within a few per cent of that of standard methods over a wide range of DGD values [6-7].

5.1.2 Measurement principle

End-to-end PMD in a fibre link may be characterized by the mean DGD, $<\Delta\tau>$, or alternatively by the RMS DGD, $<\Delta\tau^2>^{1/2}$, which is closely related to $<\Delta\tau>$. For example, $<\Delta\tau>$ can be readily determined by measuring the DGD, $\Delta\tau$, at various optical frequencies across the transmission band and averaging the results (see also IEC 61280-4-4). However, $<\Delta\tau>$ may also be obtained by averaging a set of $\Delta\tau$ measurements which are taken at the same optical frequency and repeated several times over a sufficiently long time interval, or from the average of a set of $\Delta\tau$ measurements taken at different times and frequencies [6, 14]. In either case, such DGD measurements typically require a special probe signal as well as knowledge or even control of the launch polarization state of the probe signal, whereas commercial WDM signals are usually launched with arbitrary polarization states which may not be controlled, varied or aligned.

The PMD-induced waveform distortion or pulse spreading in a WDM signal with arbitrary launch SOP depends on the orientation of the launch SOP relative to the usually unknown and randomly oriented input principal state of polarization (PSP) of the fibre at the signal wavelength. It may be characterized by a parameter commonly referred to as “effective” or “partial” DGD, $\Delta\tau_{eff}$ This quantity is defined as the magnitude of the component of the PMD vector in Stokes space that is orthogonal to the launch polarization state of the optical signal [6, 15]. Its relation to the instantaneous DGD $\Delta\tau$ is

$$\Delta\tau_{eff} = \Delta\tau \sin\varphi \tag{1}$$

wherein φ denotes the aforementioned angle between the Stokes vectors representing the launch SOP of the signal and the input PSP of the fibre.

It is easily seen that $\Delta\tau_{eff} = \Delta\tau$ if the launch SOP is an equal mix of the two input PSPs, and $\Delta\tau_{eff} = 0$ if the launch SOP is identical with one of the two PSPs. For fibre links having