IEC TR 61282-5

Edition 2.0 2019-07

TECHNICAL REPORT

Fibre optic communication system design guidelines –
Part 5: Accommodation and compensation of chromatic dispersion

IEC TR 61282-5:2019-07(en)

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

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

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 33.180.01

ISBN 978-2-8322-7131-5

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDELINES –

Part 5: Accommodation and compensation of chromatic dispersion

FOREWORD

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The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a Technical Report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC TR 61282-5, which is a Technical Report, has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

This second edition cancels and replaces the first edition, published in 2002, and constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) extends the application space for dispersion compensation and accommodation to communication systems that employ non-zero dispersion-shifted fibres;
b) adds a discussion on the suitability of fibre types for long-haul transmission of wavelength-multiplexed signals;
c) updates the dispersion coefficient limits for dispersion-unshifted fibres;

d) adds information on the dispersion coefficients of dispersion-shifted fibres;

e) updates the naming of the fibre types to the revised naming conventions defined in IEC 60793-2-50:2018;

f) updates Table 2 to include the dispersion tolerance of phase-shift-keyed modulation formats used for the transmission of 40 Gbit/s and 100 Gbit/s signals;

g) adds information on dispersion management in terrestrial and submarine communication systems;

h) extends the description of passive dispersion compensators based on fibre Bragg gratings and etalons;

i) adds information on electronic dispersion accommodation in coherent communication systems (including transmitters and receivers);

j) updates the description of optical accommodation techniques to include soliton transmission and mid-span spectral inversion;

k) extends the list of system parameters for passive dispersion compensators to include wavelength-dependent loss, phase ripple, and latency;

l) updates the description of dispersion compensator applications in long-haul communication systems.

The text of this Technical Report is based on the following documents:

Draft TR	Report on voting
86C/1573/DTR	86C/1581/RVDTR

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 61282 series, published under the general title *Fibre optic communication system design guidelines*, can be found on the IEC website.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

The committee has decided that the contents of this document 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 document. At this date, the document 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 GUIDELINES –

Part 5: Accommodation and compensation of chromatic dispersion

1 Scope

This part of IEC 61282, which is a Technical Report, describes various techniques for accommodation and compensation of chromatic dispersion in fibre optic communication systems. These techniques include dispersion compensation with passive optical components, advanced dispersion management, and electronic accommodation of dispersion in the transmitters and receivers.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

No terms and definitions are listed in this document.

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 Abbreviated terms

ADC	analogue-to-digital converter
BER	bit-error ratio
CD	chromatic dispersion
CW	continuous wave
DAC	digital-to-analogue converter
DCF	dispersion-compensating fibre
DCM	dispersion compensation module
DGD	differential group delay
DPSK	differential phase-shift keying
DQPSK	differential quaternary phase-shift keying
DSF	dispersion-shifted fibre
DWDM	dense wavelength-division multiplexing
FBG	fibre Bragg grating
FWM	four-wave mixing
I	in-phase component
IL	insertion loss
ITU	International Telecommunication Union

LO	local oscillator
MLSE	maximum-likelihood sequence estimation
NRZ	non-return-to-zero
NZDSF	non-zero dispersion-shifted fibre
OA	optical amplifier
OOK	on-off keying
OSNR	optical signal-to-noise ratio
PAM	pulse-amplitude modulation
PBS	polarization splitter
PCD	pre-compensated dispersion
PD	photo-detector
PDC	passive dispersion compensator
PDL	polarization-dependent loss
PMD	polarization-mode dispersion
PSK	phase-shift keying
Q	quadrature-phase component
QAM	quadrature amplitude modulation
QPSK	quaternary phase-shift keying
RD	residual dispersion
RDPS	residual dispersion per span
RMS	root-mean-square
Rx	optical receiver
RZ	return-to-zero
SPM	self-phase modulation
TIA	transimpedance amplifier
Tx	optical transmitter
WDL	wavelength-dependent loss
WDM	wavelength-division multiplexing
XPM	cross-phase modulation
XPolM	cross-polarization modulation
XI	in-phase component of X-polarized signal
XQ	quadrature-phase component of X-polarized signal
YI	in-phase component of Y-polarized signal
YQ	quadrature-phase component of Y-polarized signal

4 Background

Optical communication fibres often exhibit a considerable amount of chromatic dispersion (CD). This means that optical signals at different wavelengths propagate at different speeds through the fibre and, hence, arrive at different times at the receiver. In some communication links, the fibre dispersion can be large enough to also introduce significant differential time delays between the various frequency components forming a single modulated optical signal. These time delays may cause severe waveform distortions in the transmitted optical signal. Chromatic dispersion accumulates linearly with fibre length and, hence, can severely limit the maximal distance over which an optical signal may be transmitted without intermediate electrical regeneration.

To overcome these distance limitations, special fibres have been developed that exhibit relatively small or even negligible dispersion in the wavelength range of interest. It was found, however, that fibres with vanishing dispersion are not well suited for long-haul communication systems employing dense wavelength-division multiplexing (DWDM) because of signal distortions due to nonlinear optical interactions between the various multiplexed signals, such as cross-phase modulation (XPM) and four-wave mixing (FWM). In fibres with relatively large CD, the nonlinear signal distortions accumulate much more slowly than in fibres with only small or even vanishing CD. The reason is that dispersion introduces differential time delays between the various multiplexed signals as they travel through the fibre, which have the effect that they de-phase the nonlinear interactions between the signals. For this reason, DWDM communication systems usually employ fibres that have non-vanishing dispersion in the wavelength range of interest.

If not properly compensated or otherwise accommodated, the accumulated dispersion at the end of the fibre link may cause severe signal distortions in the transmitted signals, especially in long-haul communication systems and for signals that are modulated at symbol rates of 10 GBd or higher. Without dispersion compensation, the maximal transmission distances decrease rapidly with increasing modulation rate of the transmitted signals.

Techniques for reducing the waveform distortions caused by accumulated CD include the insertion of passive optical elements with opposite dispersion along the fibre link (optical dispersion compensation), dispersion-assisted transmission of optical signals (soliton pulses), and electrical accommodation of CD-induced waveform distortions in the optical transmitters and receivers (pre- and post-compensation). Optical compensation techniques are primarily applied in medium- to long-haul DWDM transmission systems using direct-detection (i.e. non-coherent) receivers, whereas electrical accommodation techniques are widely employed in transmission systems using coherent receivers and complex vector modulation.

Depending on the fibre type, short-reach communication systems, in particular those operating in the 1 300-nm wavelength range, may not require dispersion mitigation, because of their short length (typically less than 10 km) and small dispersion coefficient.

5 Impact of chromatic dispersion

5.1 Dependence on fibre type

Chromatic dispersion in optical communication fibres is usually characterized by a length-independent dispersion coefficient $D(\lambda)$, expressed in units of ps/(nm·km) or ps/nm-km. The total amount of dispersion in a fibre of length L is given by $D(\lambda)\times L$ and, hence, increases linearly with fibre length. The magnitude and sign of the dispersion coefficient generally vary with optical wavelength λ and can differ substantially from fibre type to fibre type.

The various fibre types used in single-mode optical communication links are categorized in IEC 60793-2-50 according to their design and dispersion characteristics. They include dispersion-unshifted fibres as well as various types of dispersion-shifted fibres. IEC 60793-2-50 also specifies acceptable ranges for the dispersion coefficients $D(\lambda)$ of these fibres, which mirror those specified in ITU-T Recommendations G.652 through G.657 for single-mode fibres and cables [1] to [6].

The amount of distortion caused by chromatic dispersion in a transmitted optical signal thus depends on the fibre type, the length of the fibre, and the wavelength of the signal. The magnitude and wavelength dependence of $D(\lambda)$ for the various fibre types and their impact on signal transmission is discussed in 5.2 and 5.3.

5.2 Dispersion-unshifted fibres

The first generation of single-mode fibres used in optical communication systems were dispersion-unshifted fibres, which are defined in IEC 60793-2-50 as category B-652 fibres (formerly known as category B1 fibres). Although originally intended for signal transmission around 1 310 nm wavelength, B-652 fibres are also frequently used in the 1 550-nm range, where the optical attenuation coefficient is significantly smaller than at 1 310 nm. The dispersion coefficient of these fibres vanishes at some wavelength around 1 310 nm, called the zero-dispersion wavelength λ_0, but becomes fairly large at wavelengths around 1 550 nm. As for most fibre types, the zero-dispersion wavelength and the wavelength dependence of the dispersion coefficient $D(\lambda)$ may differ from fibre to fibre because of variations in the fibre design and the manufacturing process.

IEC 60793-2-50 specifies the acceptable variations in the zero-dispersion wavelength λ_0 and the slope of the dispersion coefficient, thus setting boundaries for the dispersion coefficient $D(\lambda)$ as a function of wavelength [7] [8]. This is shown in Figure 1 for the example of sub-category B-652.D fibres. The solid curve displays the maximal values allowed for $D(\lambda)$, while the dashed curve shows the corresponding minimal values. At 1 310 nm wavelength, the dispersion coefficient is bound between –1,3 ps/nm-km and +0,9 ps/nm-km, whereas it increases to at least 13,3 ps/nm-km but no more than 18,6 ps/nm-km at 1 550 nm. Other types of dispersion-unshifted fibres may have slightly different limits for $D(\lambda)$.

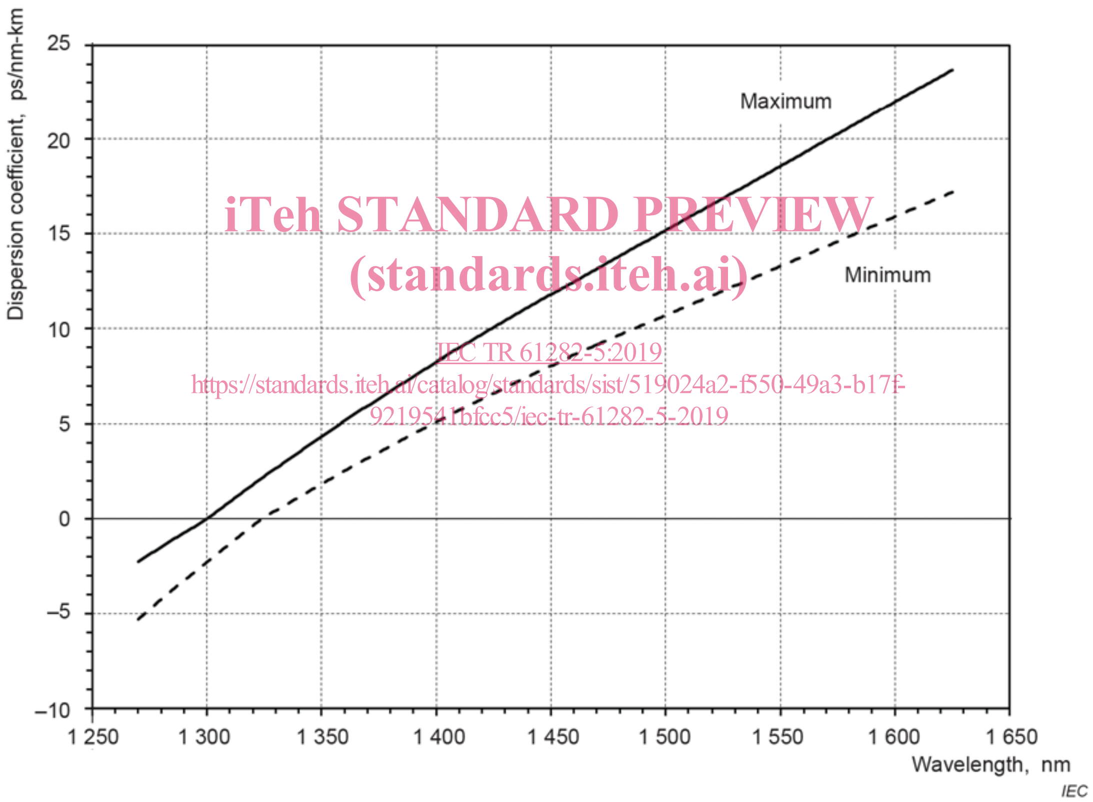

Figure 1 – Range of the dispersion coefficient for B-652.D fibres

Short-reach communication systems (with less than 40 km transmission distance) using category B-652 fibres and signal sources around 1 300 nm wavelength may not be impacted by CD, whereas medium- and long-haul communication systems operating in the C-band (1 530 nm to 1 565 nm) or in the L-band (1 565 nm to 1 625 nm) can be severely affected by CD because of the higher dispersion coefficient and longer length.

At 1 550 nm wavelength, a dispersion coefficient of around 17 ps/nm-km may be considered typical for dispersion-unshifted fibres. Thus, in a 100-km long fibre link, the accumulated dispersion is about 1 700 ps/nm. Insertion of a properly selected optical dispersion compensator can decrease this value to about 100 ps/nm or less. However, in DWDM applications, the slope of the dispersion coefficient also becomes important. Around 1 550 nm, the dispersion-slope coefficient is about 0,057 ps/nm^2-km, which means that the accumulated dispersion in a 100-km long link typically increases by about 200 ps/nm between 1 530 nm and 1 565 nm wavelength.

5.3 Dispersion-shifted fibres

Fibre dispersion is the sum of material and waveguide dispersion. It is therefore possible to move the zero-dispersion wavelength λ_0 of a fibre to a different value by changing the waveguide dispersion in the light-guiding fibre core. Shifting λ_0 to longer wavelengths typically reduces the dispersion coefficient in the 1 550-nm range. These types of fibres are known as dispersion-shifted fibres (DSFs). In category B-653 fibres (formerly category B2 fibres), the zero-dispersion wavelength is shifted to around 1 550 nm, as specified in IEC 60793-2-50. Consequently, the magnitude of the dispersion coefficient in B-653 fibres is very small across the C-band.

Transmission of DWDM signals over zero- or low-dispersion fibres can be severely impaired by nonlinear optical interactions between the various optical channels which occur along the fibre link, as described in IEC TR 61282-4 [9]. These non-linear interactions manifest themselves in cross-phase modulation (XPM), cross-polarization modulation (XPolM), and four-wave mixing (FWM). It was found that signal distortions caused by XPM, XPolM and FWM accumulate much more slowly in fibres with large dispersion coefficients than in those with small or nearly vanishing dispersion coefficients [10]. Therefore, B-653 fibres are not suitable for long-haul transmission of DWDM signals in the C-band, although they may be used for DWDM transmission in the L-band, where the dispersion coefficient is significantly larger. For this reason, B-653 fibres are no longer deployed in long-haul optical communication systems.

Newer generations of dispersion-shifted fibres are designed to have relatively small but non-vanishing dispersion coefficients within the C-band, so as to allow DWDM transmission over long fibre links. In these non-zero dispersion-shifted fibres (NZDSF), defined as category B-655 fibres in IEC 60793-2-50 (formerly category B4), λ_0 is shifted either to a wavelength below 1 530 nm, so that $D(\lambda)$ is greater than zero in the entire C-band, or to one above 1 565 nm, so that $D(\lambda)$ is lower than zero in the C-band. Since fibres with λ_0 > 1 565 nm do not support DWDM transmission in the L-band (1 565 nm to 1 625 nm), newer generations of NZDSFs, like sub-category B-655.D fibres, specify λ_0 to be below 1 530 nm, so that $D(\lambda)$ is greater than zero in the C- and L-bands. In category B-656 fibres (formerly category B5), which were designed for wideband optical transport networks, λ_0 is shifted to below 1 460 nm, so that $D(\lambda)$ is greater than zero over the extended wavelength range from 1 460 nm to 1 625 nm, covering the S-, C- and L-bands. Consequently, category B-656 fibres exhibit significantly larger dispersion at 1 550 nm than some of the earlier generations of NZDSF.