# 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

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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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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,
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- 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 $\lambda$ 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 $\lambda_0$, 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 $\lambda_0$ 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 $D(\lambda)$.

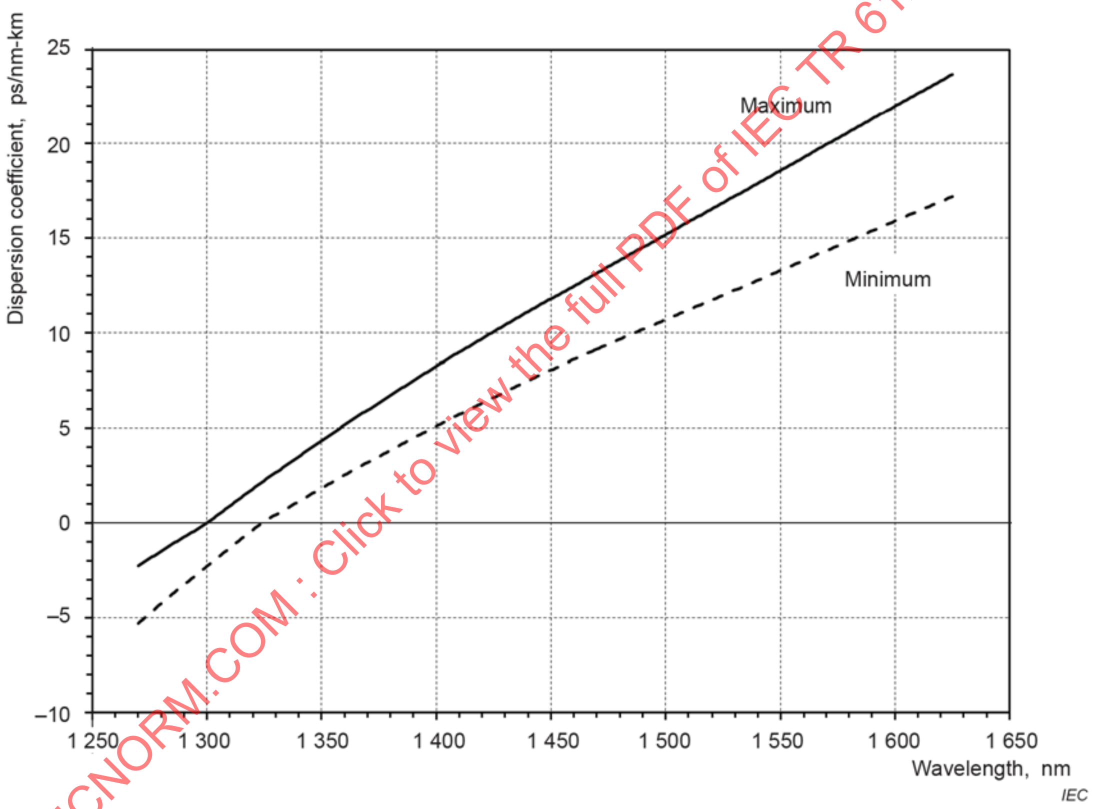





**Figure 1 – Range of the dispersion coefficient for B-652.D fibres**

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 $\lambda_0$ of a fibre to a different value by changing the waveguide dispersion in the light-guiding fibre core. Shifting $\lambda_0$ 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), $\lambda_0$ 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 $\lambda_0$ > 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 $\lambda_0$ 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, $\lambda_0$ 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.

**Table 1 – Single-mode fibre types and range of dispersion coefficients at 1 550 nm**

| Fibre type | IEC category | | $D(\lambda)$ at 1 550 nm ps/nm-km | | |
|---|---|---|---|---|---|
| | Old[a] | New[b] | Example | Min. | Max. |
| Dispersion-unshifted | B1.1 | B-652.B | B-652.B | - | 18[c] |
| Cut-off shifted | B1.2 | B-654 | B-654.E | 17 | 23 |
| Dispersion-unshifted (reduced water peak) | B1.3 | B-652.D | B-652.D | 13,3 | 18,6 |
| Bending-loss insensitive | B6 | B-657 | B-657.A | 13,3 | 18,6 |
| Dispersion-shifted | B2 | B-653 | B-653.B | –2,3 | +2,3 |
| Non-zero dispersion-shifted | B4 | B-655 | B-655.E | 6,1 | 9,3 |
| Wideband non-zero dispersion-shifted | B5 | B-656 | B-656 | 3,6 | 9,3 |

NOTE The minimal and maximal dispersion coefficients are listed for illustrative purposes and apply only to the specified sub-categories. The dispersion ranges for other fibre sub-categories and/or at other wavelengths can be found in IEC 60793-2-50.

[a] IEC 60793-2-50:2015 and older [7].

[b] IEC 60793-2-50:2018 and newer [8].

[c] Calculated from the minimal zero-dispersion wavelength and the maximal zero-dispersion slope according to [1].



Table 1 lists examples of the various types of dispersion-unshifted and dispersion-shifted fibres and their specifications for minimal and maximal dispersion coefficients at 1 550 nm. Thus, even with non-zero dispersion-shifted fibres, the total accumulated chromatic dispersion at the end of a long fibre link may become too large to allow error-free transmission in long-distance communication links. In this case, it is necessary to either compensate the fibre CD by inserting optical dispersion compensators or otherwise accommodate its effects.

## 5.4 Pulse broadening

Fibre dispersion generally leads to waveform distortions in the transmitted optical signal, which include pulse broadening as well as signal peaking, as discussed in 5.5. The reason for these waveform distortions is that the various frequency components of a modulated signal travel at different speeds through the fibre and, hence, arrive at different times at the end of the fibre link. The differential time delay $\Delta t$ between two signals at different wavelengths is proportional to their wavelength difference $\Delta\lambda$ and the total dispersion in the fibre link, which is determined by the dispersion coefficient $D(\lambda)$ and fibre length $L$ [11]:

$$\Delta t(\lambda) = D(\lambda) \times L \times \Delta\lambda \quad (1)$$

A positive dispersion coefficient means that longer wavelengths experience longer transit times than shorter wavelengths. For negative dispersion coefficients, the order is reversed, so that longer wavelengths experience shorter transit times than shorter wavelengths.

The optical spectrum of a modulated signal always has a finite spectral width $\Delta\lambda_m$ and, hence, contains a multitude of wavelengths, which all experience different time delays when traveling through a dispersive fibre. If these time delays become too large, they can severely distort the waveform of the transmitted signal. The differential phase shifts $\Delta\phi$ introduced by the CD-induced time delays can be described in the wavelength domain by a simple multiplication of the complex spectral components with the complex transfer function:

$$H(\Delta\lambda) = \exp\left\{j\Delta\phi(\Delta\lambda)\right\} = \exp\left\{j\frac{\pi\times\Delta t(\lambda)\times c\times\Delta\lambda}{\lambda^2}\right\} = \exp\left\{j\frac{\pi\times D(\lambda)\times L\times c\times\Delta\lambda^2}{\lambda^2}\right\} \quad (2)$$

where

$c$ is the speed of light in vacuum;

$\Delta\lambda$ is the wavelength difference between each spectral component and the centre frequency of the spectrum [11].

Thus, the wider the modulated optical spectrum is, the larger $\Delta\phi$ can be. It is important to note that $\Delta\phi$ grows proportionally with $\Delta\lambda^2$, which means that the dispersion-induced waveform distortions increase steeply with the width of the modulated optical spectrum $\Delta\lambda_m$ and thus with the modulation rate of the optical signal.

For example, a binary non-return-to-zero on-off-keyed signal (NRZ-OOK) at bit-rate $B$ carries significant spectral content in a frequency interval of $2B$. For $B$ = 10 Gbit/s and $\lambda$ = 1 550 nm, this interval corresponds to a spectral width of $\Delta\lambda_m$ = 0,16 nm, whereas for $B$ = 40 Gbit/s, $\Delta\lambda_m$ is four times larger, i.e. 0,64 nm. However, the CD-induced maximal differential phase shifts in the optical spectrum increase with the square of $B$, as described by Equation (2). For this reason, a binary 40 Gbit/s NRZ-OOK signal is 16 times more sensitive to CD than a binary 10 Gbit/s NRZ-OOK signal, and 256 times more sensitive than a binary 2,5 Gbit/s NRZ-OOK signal.

In most instances, the CD-induced differential phase shifts $\Delta\phi$ lead to pulse broadening in digital communication systems and to modulation-frequency roll-off in analogue communication systems. This can be better seen in the time domain, where the transfer function $H(\Delta\lambda)$ corresponds to a convolution of the time-varying optical signal amplitude $A(t)$ with the complex transfer function:

$$h(t) = \frac{1}{\sqrt{\alpha}}\exp\left\{-j\frac{t^2}{2\alpha}\right\} \quad (3)$$

where

$\alpha$ = $D(\lambda)$ x $L$ x $\lambda^2$/(2 x $\pi$ x $c$)

When applied to a single chirp-free optical pulse, this convolution simply spreads the optical energy of the pulse in time and thus lengthens the pulse duration. However, the waveform distortions of modulated optical signals tend to be more complicated, because the pulse distortion of each individual symbol depends on the amplitudes and phases of the preceding and succeeding symbols. As a result, the waveform distortions become pattern-dependent (as in Figure 2) and may exhibit pulse broadening and pulse narrowing as well as signal peaking. The larger the accumulated dispersion, the more symbols are involved in the convolution.

The dispersion-induced waveform distortions depend on the overall width of the optical spectrum, which is determined by the information content of the digital or analogue information to be transmitted as well as by the particular modulation format used to encode the optical signal. For a given modulation format, the spectral width increases linearly with the modulation frequency (in analogue systems) or the symbol rate (in digital systems). In general, binary encoded signals have broader optical spectra than those using modulation formats of higher cardinality, such as quaternary pulse-amplitude-modulated (PAM-4) or quaternary phase-shift keyed (QPSK) signals. However, polarization-multiplexed signals have the same spectral width than single-polarized signals of the same modulation format and symbol rate.

The optical spectrum may be further broadened by frequency chirping and nonlinear modulation in the transmitter, as discussed in 5.5, or by the finite spectral width of the unmodulated light source in the transmitter. However, the latter is usually negligible, because long-haul communication systems operating at bit rates of 10 Gbit/s or above generally employ single-longitudinal-mode lasers with linewidths below 100 MHz.

### 5.5 Pulse narrowing and signal peaking

The dispersion-induced waveform distortions are affected by frequency chirping and nonlinear modulator response in the optical transmitter. Chirping can occur, particularly in directly modulated lasers, where the digital or analogue modulation signal is directly applied to the laser drive current. This type of modulation may cause the laser wavelength to vary with time. In digital transmission systems, for example, the laser wavelength may move towards shorter wavelengths during the ramp-up of the pulse and back towards longer wavelengths during ramp-down (positive chirp). This frequency chirping causes significant broadening of the modulated spectrum as well as further broadening of the transmitted pulses at the end of a fibre with positive dispersion, because the leading edges of the pulses have shorter wavelengths and hence arrive sooner than the trailing edges, which have longer wavelengths.

Conversely, in the negative dispersion region (at wavelengths below $\lambda_0$), positive chirping can result in pulse narrowing. Therefore, significant pulse compression can occur after certain fibre lengths, but then the pulses broaden again. Therefore, proper frequency chirping can extend the dispersion-limited transmission distance [12]. A similar effect can be achieved with negative frequency chirp when the fibre dispersion is positive. This technique is an example of dispersion accommodation discussed in 6.4.

Chirping can be alleviated or completely avoided when using an external modulator in conjunction with an unmodulated (continuous-wave) laser. A semiconductor electro-absorption modulator normally exhibits significantly less chirp than a directly modulated laser but introduces considerable insertion loss. High-speed transmission systems at bit rates of 10 Gbit/s and beyond frequently use electro-optic modulators based on Mach-Zehnder interferometers, which can be designed to introduce negligible frequency chirp or, if so desired, a fixed amount of positive or negative chirp.

In general, the optical output amplitude of interferometric Mach-Zehnder modulators is not a linear function of the modulating drive signal, particularly when the modulator is swept from the completely-on state to the completely-off state. Such nonlinear modulation generates harmonic frequency components in the modulated spectrum, which can cause significant signal peaking and even pulse narrowing after experiencing fibre dispersion. Figure 2 displays simulations of CD-induced waveform distortions in a 10 Gbit/s NRZ-OOK signal generated with a chirp-free interferometric Mach-Zehnder modulator. Pulse narrowing can be observed in the isolated “1” symbols when the signal has experienced moderate amounts of CD, i.e. 670 ps/nm and 1 340 ps/nm, corresponding to about 40 km and 80 km of dispersion-unshifted fibre, which is caused by clock frequency components in the optical amplitude spectrum [13]. After larger amounts of accumulated CD (i.e. above 2 000 ps/nm), the initial pulse narrowing of the isolated “1” symbols has turned into pulse broadening, but the signal peaking in the broader pulses (formed by several consecutive “1” symbols) has grown even larger.

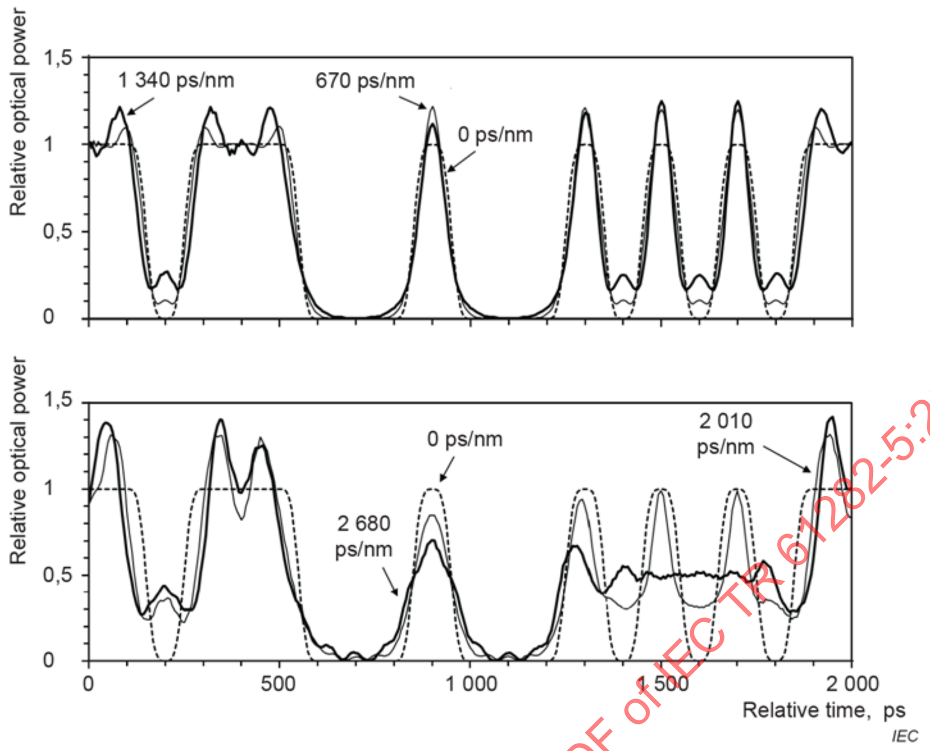



**Figure 2 – Distortions in a 10 Gbit/s NRZ signal at various amounts of CD**

Dispersion-induced signal peaking tends to be larger in on-off keyed signals than in phase-shift keyed signals. In either case, it can cause additional waveform distortions through nonlinear effects, such as self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM), which are difficult to mitigate. The nonlinear waveform distortions may be minimized through careful management of the accumulated dispersion along the fibre link, as discussed in 6.2.

### 5.6 Dispersion-limited transmission distance

Without proper compensation or accommodation, dispersion can severely limit the distance over which an optical signal may be transmitted without intermediate opto-electronic regeneration. Subclause 5.6 describes how the maximal transmission distance depends on the total amount of accumulated dispersion in the fibre link as well as on the symbol rate and modulation format of the transmitted optical signals.

For binary NRZ on-off-keyed signals, ITU-T Recommendation G.957 specifies that pulse spreading due to chromatic dispersion should not exceed a fraction $\varepsilon$ of the symbol period $1/B$ of the digital modulation [14], where $B$ denotes the modulation rate, so as to not exceed the maximal allowable dispersion power penalty at a particular bit-error ratio (BER). For a 1 dB power penalty at a BER of $10^{-10}$, the value of $\varepsilon$ is about 0,3. It should be noted that $\varepsilon$ depends upon certain component parameters of the transmission equipment and, therefore, should be individually determined for each system design.

With $\Delta t = \varepsilon / B$, one can then calculate the dispersion-limited maximal transmission distance $L_D$ for binary NRZ signals from Equation (1). Neglecting the spectral width of the unmodulated light source, $L_D$ is approximately given by:

$$L_D = \frac{\varepsilon}{B \times D \times 2\Delta\lambda_m} \qquad (4)$$

where

$\Delta\lambda_m$ = $\frac{\sqrt{3B\lambda^2}}{2\pi c}$ is the root-mean-square spectral width of the modulated optical spectrum;

$D$ is the dispersion coefficient of the fibre;

$\lambda$ is the centre wavelength of the spectrum.

NOTE It is assumed that the transmission distance is not limited by fibre attenuation, optical amplifier noise, or non-linear effects in the fibre link. The maximal transmission lengths are not specified in any ITU recommendation.

Table 2 provides examples of the maximal accumulated chromatic dispersion $D \times L$ that can be tolerated in modulated optical signals of various bit-rates and modulation formats, as well as the corresponding dispersion-limited transmission lengths over uncompensated category B-652 fibre, assuming $D(\lambda)$ = 17 ps/nm-km at 1 550 nm. These data assume chirp-free modulation and an ideal light source having negligible spectral width when unmodulated [15].

**Table 2 – Dispersion-limited transmission distances over B-652 fibre at 1 550 nm**

| Maximal dispersion and transmission distance | Bit rate and modulation format | | | | | |
|---|---|---|---|---|---|---|
| | 2,5 Gbit/s NRZ-OOK (OTU1/ STM-16) | 10 Gbit/s NRZ-OOK (OTU2/ STM-64) | 40 Gbit/s NRZ-DPSK (OTU3/ STM-256/ 40GbE) | 40 Gbit/s RZ-DQPSK (OTU3/ STM-256/ 40GbE) | 40 Gbit/s PM-(D)QPSK (OTU3/ STM-256) | 100 Gbit/s PM-(D)QPSK (OTU4/ 100GbE) |
| Maximal chromatic dispersion for 2 dB OSNR penalty | 13 500 ps/nm | 850 ps/nm | 80 ps/nm | 170 ps/nm | 700 ps/nm[a] | 100 ps/nm[a] |
| Dispersion-limited distance over B-652 fibre | 800 km | 50 km | 5 km | 10 km | 40 km[a] | 6 km[a] |

NOTE The dispersion-limited transmission distance strongly depends on the details of the transmission equipment and, hence, can significantly vary from system to system. The numbers listed in this table are only approximate values intended to illustrate the general dependence on modulation rate and format.

[a] Without dispersion accommodation in the receiver or transmitter.



The dispersion-limited transmission distance is determined by the total accumulated dispersion which the signal has experienced when it arrives at the receiver. This distance decreases with increasing symbol rate of the modulated signal, but not necessarily with increasing bit rate. The dispersion-limited distance of 40 Gbit/s polarization-multiplexed QPSK signals, for example, is comparable to that of 10 Gbit/s NRZ-OOK signals, because both signals are modulated at the same symbol rate and, hence, exhibit similar spectral widths. In general, QPSK signals are somewhat more sensitive to CD than binary coded OOK signals. Communication systems transmitting complex, vector-modulated signals (e.g. 40 Gbit/s QPSK or 100 Gbit/s QPSK) often employ coherent optical receivers, which can accommodate large amounts of accumulated dispersion, as described in 6.5, in some cases up to 50 000 ps/nm or even more [16]. Hence, the dispersion-limited transmission lengths of these systems are substantially larger than the ones listed in Table 2. Long-haul communication systems operating at 100 Gbit/s or higher therefore often employ coherent receivers.

If the total accumulated dispersion in a fibre link is reduced by means of optical dispersion compensation, the maximal transmission lengths will increase substantially. As can be seen from Table 2, dispersion compensation is essential for long-haul transmission of 10 Gbit/s NRZ-OOK signals and even more so for 40 Gbit/s NRZ-DPSK and 40 Gbit/s RZ-DQPSK signals. For the latter, optical dispersion compensation is needed even if the signals are transmitted over relatively short distances or over non-zero dispersion-shifted fibres. However, optical dispersion compensators generally exhibit considerable optical insertion loss, which may have to be compensated for by optical amplification. Hence, optical dispersion compensators and optical amplifiers are complementary, because they both increase the maximal transmission lengths.

When large fibre dispersion is optically compensated (e.g. by passive dispersion compensators), the maximal transmission length may be limited not only by first-order chromatic dispersion but also by second-order dispersion. The more general form of Equation (1) is:

$$\Delta t(\lambda) = L \cdot \Delta\lambda_m \sqrt{D^2(\lambda) + \frac{1}{2}\left\{\left[S(\lambda) + 2\frac{D(\lambda)}{\lambda}\right]^2 \cdot \Delta\lambda_m{}^2\right\}} \quad (5)$$

where

$S(\lambda) = \frac{d\mathrm{D}(\lambda)}{d\lambda}$ is the dispersion-slope coefficient.

The importance of the second-order term depends upon the combined dispersion slope of the transmission fibre and the dispersion compensators. Second-order dispersion is also an important factor for broad-band dispersion compensation, for example across the entire C-band, which is essential for DWDM transmission according to ITU-T Recommendation G.692, because it determines the variations of the compensated dispersion over the desired wavelength range [17].

# 6 Compensation and accommodation of dispersion

## 6.1 Passive dispersion compensation along the optical path

### 6.1.1 General

Passive optical dispersion compensation refers to techniques that reduce the total accumulated dispersion or dispersion slope of a fibre optic link by insertion of dispersion-compensating optical components at various locations along the fibre link. These components may be dispersion-compensating fibre (DCF), specially designed fibre Bragg gratings, or etalon-based filters [11] [18].

Passive dispersion compensators (PDCs) generally reduce or even reverse the accumulated differential delays between the faster shorter wavelengths and the slower longer wavelengths. Fixed PDCs are available to compensate the dispersion of various lengths and types of fibre, whereas variable PDCs are less frequently needed to fine-tune the compensation at the receiver. PDCs may be inserted at the transmitter or receiver, or at various places along the optical path. Non-linear effects in the fibre may determine their optimal placement, as discussed in more detail in 6.2.

Properly packaged PDCs are often referred to as dispersion compensation modules (DCMs). DCMs may contain either FBG-based PDCs or spools of dispersion compensating fibre.

### 6.1.2 Dispersion compensating fibre

Dispersion-compensating fibre (DCF) is the most-widely used PDC, since it has the advantage of polarization insensitivity, low dispersion ripple, and wide optical bandwidth. DCFs for B-652 fibre typically have negative dispersion as well as negative dispersion slope, both tailored by the material and design of the fibre core. The dispersion coefficient of DCFs typically is multiple times larger than that of the transmission fibre (although of opposite sign), and the attenuation coefficient is slightly larger. Hence, the length of DCF needed to compensate the CD of a certain span of transmission fibre is only a small fraction of the length of the transmission span. However, DCFs usually feature significantly smaller mode sizes than ordinary transmission fibres. As a result, the power threshold for nonlinear signal interactions is usually considerably lower in DCFs than in regular transmission fibres.

Figure 3 shows an example of how the dispersion of a DCF-based PDC and a length of dispersion-unshifted fibre add across the C-band. In the example shown, the compensator has a negative dispersion slope to counteract the positive dispersion slope of the transmission fibre. This flattens the total dispersion, which is essential for DWDM applications.

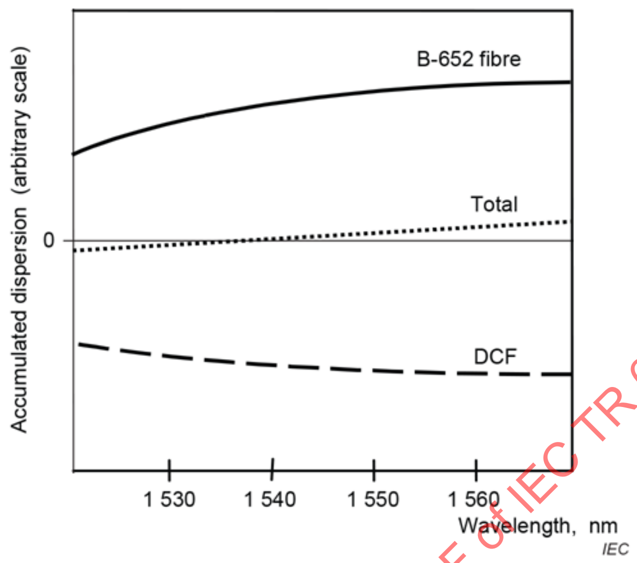
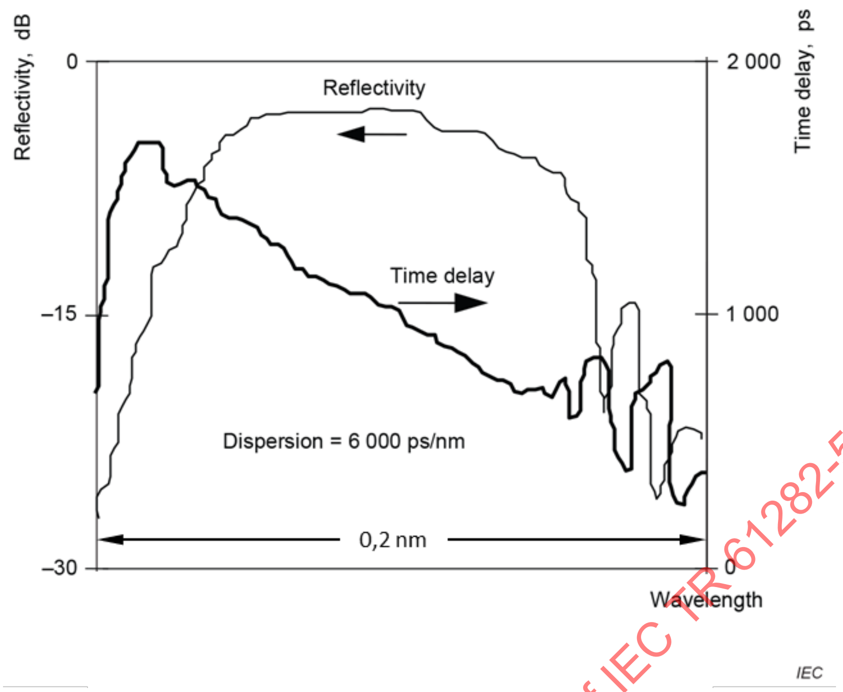



**Figure 3 – Summing the dispersions of a B-652 fibre and a DCF over the C-band**

### 6.1.3 Chirped fibre Bragg grating

PDCs based on fibre Bragg gratings (FBGs) consist of relatively short pieces of fibre along which the refractive index varies periodically. The period of this grating is chirped in such a way that shorter wavelengths travel further than longer wavelengths before being reflected by the shorter-period portion of the grating, which results in a time delay with respect to the longer wavelengths. Most FBG-based PDCs operate in reflection, although there are also designs for operation in transmission. For reflective-type gratings, an optical circulator is used to separate input and output light of the PDC. In any case, the differential time delays that can be generated with FBGs are fairly small, which means that they can compensate CD only over a limited optical bandwidth. FBGs typically have passbands that are narrower than the spectral width of a DWDM channel, as shown in the example of Figure 4.




NOTE The dispersion is calculated from the slope of the time delay in the centre of the transmission band.

**Figure 4 – Reflectivity and time delay of an FBG-based PDC**



Most FBG-based PDCs have multiple passbands across the C- or L-band, which are separated by opaque guard bands. The various passbands are generated by superimposing several Bragg gratings with different pitch and chirp in a single device. Note that these "channelized" PDCs are not compatible with flexible DWDM channel grids, as defined in ITU-T Recommendation G.674.1 [19]. It is possible, however, to manufacture FBG-based PDCs with substantially wider passbands.

Slow- and fast-varying "ripples" may occur on the reflectivity and time delay characteristics of FBG-based PDCs. Both types of ripple may cause significant signal distortion, especially fast-varying time delay ripples, which are usually specified in terms of phase ripple [20]. However, FBG-based PDCs typically have substantially lower insertion loss than DCFs, because of their shorter lengths.

### 6.1.4 Etalon filter

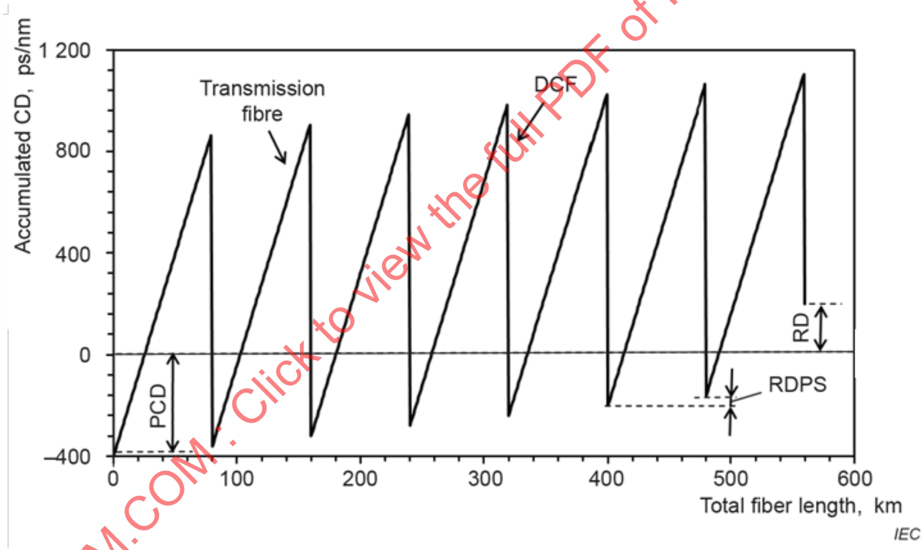
PDCs based on etalon filters also have substantially lower insertion loss than DCFs but have similar optical bandwidth limitations as "channelized" FBG-based PDCs [21]. Etalon-based PDCs are usually not compatible with flexible DWDM channel grids.

## 6.2 Dispersion management

Dispersion management refers to techniques that optimize the placement of PDCs along the fibre link to minimize signal distortion due to non-linear effects in the fibre. In relatively short fibre links of 100 km or less, the accumulated CD may simply be compensated at the end of the link by inserting a PDC just before the receiver. Alternatively, one may pre-compensate the fibre CD at the input of the fibre optic link by inserting a PDC after the transmitter. In long-haul communication systems using one or more in-line optical amplifiers, it may be necessary to also insert PDCs at various locations along the fibre link [11], [18], so as to minimize nonlinear signal distortion due to dispersion-induced signal peaking, as discussed in 5.5. These in-line PDCs are often co-located with the in-line optical amplifiers and typically placed either directly before the amplifier or, if possible, between the pre-amplifier and the booster stage of a multi-stage amplifier, as discussed in 8.2.

The transmission quality of a fibre link can often be optimized by careful adjustment of the amounts of dispersion pre-compensated at the transmitter, compensated in-line along the fibre link, and post-compensated at the receiver. This optimization is known as "dispersion management". The resulting variation of the accumulated dispersion along the fibre link is referred to as a "dispersion map". The optimal dispersion map for a communication link generally depends on the fibre type, the modulation rate and format of the transmitted signal(s) as well as the number of transmitted DWDM signals, and the type of dispersion compensators. The optimal map may be found with the help of numerical simulations or by experiment.

Figure 5 shows an example of a typical dispersion map for terrestrial communication systems, in which the dispersion is periodically compensated after each amplifier span. Typically, a small amount of dispersion is pre-compensated at the transmitter (PCD), and the dispersion in each amplifier span is either slightly under-compensated (as in Figure 5) or over-compensated, yielding a finite amount of residual uncompensated dispersion per span (RDPS). The latter is important for DWDM systems, so as to avoid a complete reset of the dispersion-induced differential time delays between the various multiplexed signals. Letting the dispersion-induced differential time delays gradually grow, as in the example of Figure 5, reduces accumulation of repeated cross-phase modulation between the same transmitted symbols. In relatively long fibre links, the accumulated RDPS may become so large that it has to be compensated after a certain number of spans, which leads to double-periodic dispersion maps [22]. Furthermore, because of nonlinear waveform distortions, it is often better to not completely remove all uncompensated dispersion at the receiver, but to leave some residual dispersion (RD) in the transmitted signals.




**Key**

PCD pre-compensated dispersion at transmitter

RDPS residual dispersion per fibre span

RD residual dispersion at receiver

**Figure 5 – Periodic dispersion map with span-by-span compensation**

Submarine communication systems usually employ specially designed transmission fibres for in-line dispersion compensation, to avoid the additional optical loss of PDCs [23]. For example, the fibre spans between amplifiers may be composed of two different fibre types, with the fibre in the first part of the span having a positive dispersion coefficient and that in the second part a negative one, so that all or most of the dispersion in the first part of the span is compensated by the dispersion in the second half of the span. Because the dispersion slopes of the two fibre types often are not perfectly matched (analogous to the situation shown in Figure 3), it may not be possible to simultaneously optimize the dispersion map for all DWDM channels in an ultra-long submarine cable. In this case, each wavelength channel may need a different PDC at the receiver for proper post-compensation of the residual dispersion. These individual PDCs are not needed when coherent optical receivers are employed, because these receivers can adaptively accommodate relatively large amounts of residual dispersion, as described in 6.5.

It should be noted that the recent introduction of coherent optical receivers in combination with advanced optical modulation formats has greatly reduced the need for in-line optical dispersion compensation in terrestrial and submarine communication systems, thus causing a paradigm shift in dispersion management. As described in 6.5, specially designed coherent receivers can accommodate the accumulated dispersion of several thousand kilometres of dispersion-unshifted fibre. Consequently, submarine communication links may be composed of just a single fibre type, which may be chosen to have a low attenuation coefficient (to improve the signal-to-noise ratio) and a large mode field diameter (to reduce nonlinear optical effects) as well as a large dispersion coefficient.

## 6.3 Accommodation of dispersion

The term "accommodation" in this document refers to electrical and optical techniques that enable high-speed signal transmission over dispersive fibres with either no or substantially less optical dispersion compensation than otherwise needed. Examples of such adaptive dispersion accommodation include electrical pre-distortion of the optical signal in the transmitter, post-compensation via digital signal processing in the receiver, dispersion-assisted signal transmission (soliton pulses), and mid-span spectral inversion.

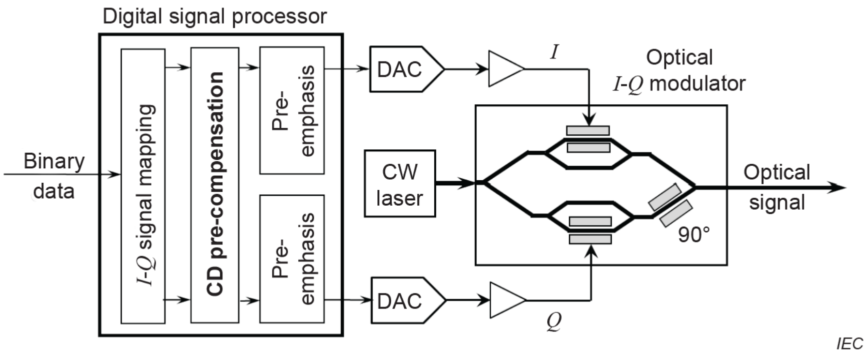
The most widely deployed accommodation technique is electrical dispersion post-compensation in the receiver. It is used in transmission systems operating at symbol rates of 10 GBd and above to accommodate residual dispersion that is not compensated by in-line PDCs. This technique is especially effective when employed in coherent optical receivers, which detect the amplitude and phase variations in the transmitted optical signal. In such receivers, it is possible to adaptively accommodate the accumulated dispersion of several thousand kilometres of dispersion-unshifted fibre, without incurring significant signal degradations. As a result, this technique reduces, and in some cases even eliminates, the need for in-line optical dispersion compensation via PDCs. With increasing symbol rates, adaptive dispersion accommodation in the receiver will become even more important for future medium- and long-haul communication systems. This technique may be complemented by dispersion accommodation in the transmitter to pre-compensate part of the accumulated dispersion in the transmission fibre.

NOTE Unless otherwise stated, it is assumed that the transmitters of the communication system employ single-frequency lasers with narrow linewidth as well optical modulators with low frequency chirp.

## 6.4 Pre-distortion of the transmitted signal

Chromatic dispersion in a fibre link may be accommodated directly in the transmitter by modulating the amplitude and phase of the optical signal in such a way that it resembles a passively pre-compensated optical signal (i.e. the output signal of a PDC placed in front of a conventional transmitter). Such pre-distorted signals can be generated in the transmitter with the help of an optical vector modulator (also known as $I$-$Q$ modulator) [24]. The desired amount of pre-compensated dispersion is obtained by pre-distorting the electrical drive signals of this modulator according to Equation (3). The higher the amount of pre-compensated CD, the more pre-distortion is required. This electronic pre-distortion technique enables adaptive accommodation of large amounts of accumulated CD without encountering the optical losses that are usually associated with PDCs. It has been shown that accumulated dispersion of up to 85 000 ps/nm can be accommodated in the transmitter [25].

The pre-distorted drive signals for the $I$-$Q$ modulator are often generated digitally by high-speed digital signal processors (DSPs) and then converted into analogue drive signals for the optical modulator, using high-speed digital-to-analogue converters (DACs), as shown schematically in Figure 6. This pre-distortion technique can be readily implemented in transmitters that generate complex, vector-modulated signals, such as QPSK or $M$-QAM signals. However, proper pre-distortion of the optical signal requires an optical modulator that has a sufficiently linear amplitude and phase response.




**Key**

DAC digital-to-analogue converter

CW continuous wave

$I$ in-phase component of signal

$Q$ quadrature-phase component of signal

**Figure 6 – Transmitter for generating pre-compensated optical signals**



If relatively large amounts of CD are to be accommodated, the DSP usually first transforms the undistorted $M$-QAM signals from the time into the frequency domain, using a discrete Fourier transformation, then multiplies the resulting frequency spectrum with the CD transfer function Equation (2), and finally transforms the spectrum back into the time domain. This process is more efficient than a convolution with Equation (3) in the time domain. The signal pre-distortion is performed in a continuous fashion, using parallel processing with sufficiently large time overlaps, so that no information is lost in the transformations. For relatively small amounts of CD, a time-domain-based convolution technique may be used instead, which pre-distorts the signals according to Equation (3), using digital finite-impulse-response filters [16].

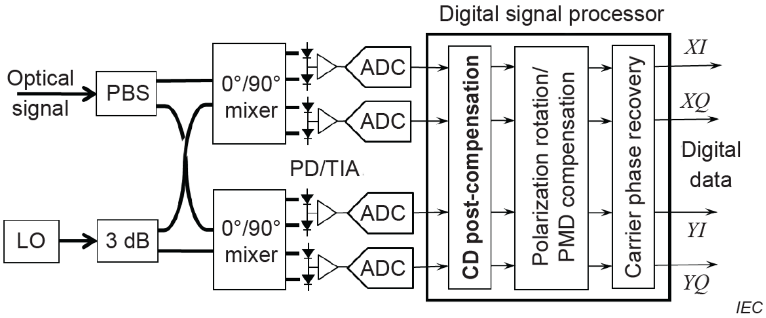
Since the CD in the fibre link may not always be known accurately enough, the pre-distortion technique is often used in conjunction with dispersion accommodation in the receiver, as described in 6.5.

If only small amounts of CD need to be accommodated, one may approximate Equation (3) by a simple frequency chirp, which has to be added to the intensity-modulated signal. Such frequency chirping is often used to pre-compensate NRZ on-off-keyed signals, as described in 5.5. A properly applied chirp has a similar effect as optical pre-compensation with a PDC. The frequency chirp may be generated by an external modulator or directly in the modulated laser [12].

## 6.5 Electrical accommodation in the receiver

Similar to pre-distortion in the transmitter, fibre dispersion may also be accommodated in the receiver at the end of the fibre link, in particular in coherent optical receivers, which are often employed in long-haul communication systems that operate at bit rates of 40 Gbit/s per channel and above.

Modern intradyne coherent receivers convert the amplitude and phase variations in the received optical signal into corresponding electrical signals, which can then be processed to remove the CD-induced waveform distortions. This is usually accomplished with the help of high-speed DSPs, after the received analogue electrical signals are converted into digital signals by high-speed analogue-to-digital converters (ADCs). To recover the transmitted information, the DSP also needs to remove waveform distortions caused by polarization mode dispersion (PMD) and polarization rotations, as well as distortions caused by frequency and phase offsets between the local oscillator and the optical signal [26], as shown schematically in Figure 7.




**Key**

| | |
|---|---|
| 3 dB | 3-dB power splitter |
| ADC | analogue-to-digital converter |
| LO | local oscillator laser |
| PBS | polarization splitter |
| PD | photo-detector |
| TIA | transimpedance amplifier |
| *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 |

**Figure 7 – Coherent optical receiver with electrical CD post-compensation**

Electrical dispersion compensation in coherent receivers is equivalent to optical post-compensation with a PDC, but does not incur the optical losses associated with a PDC. This accommodation technique allows accommodation of large amounts of CD. Specially designed coherent receivers, for example, can compensate chromatic dispersion of 100 000 ps/nm or more, which corresponds to the accumulated CD of several thousand kilometres of dispersion-unshifted B-652 fibre. Typically, the bulk of the dispersion is compensated in the frequency-domain, as described in 6.4, while any residual CD is subsequently removed in the time-domain, together with other impairments. Moreover, it is possible to estimate the amount of dispersion which the received signal has experienced and, thus, adapt the dispersion accommodation automatically to the accumulated CD in the fibre link.

Hence, electrical dispersion accommodation in coherent receivers may eliminate the need for in-line optical CD compensation in the fibre link, even in very long submarine cables. In fact, some long-distance fibre links exhibit significantly better performance when operated without in-line PDCs than those employing them, because large uncompensated fibre dispersion tends to minimize nonlinear waveform distortions due to cross-phase modulation [27]. However, to compensate such large amounts of CD requires local oscillator lasers with relatively narrow optical linewidth, so that the optical phase noise of the LO laser does not interfere with the phase-sensitive re-construction of the transmitted signals. In general, the larger the amount of accumulated CD, the narrower the LO linewidth has to be [28] [29].

Dispersion may also be accommodated in direct-detection receivers, which are commonly used in communication systems transmitting on-off-keyed signals, although to a lesser degree. Because direct-detection receivers sense only to the intensity of the received optical signal but not to its phase, they cannot completely remove the CD-induced waveform distortions from the signal [30]. Instead, these receivers use special algorithms, like maximum-likelihood sequence estimation (MLSE), to recover the transmitted information from the distorted electrical signal [31]. This accommodation technique is mostly employed in communication systems operating at 10 Gbit/s per channel. Implementation at higher bit rates becomes increasingly complex and power consuming.

## 6.6 Dispersion-assisted transmission

Dispersion-assisted transmission refers to communication systems in which chromatic dispersion is needed to successfully transmit an optical signal through a fibre span or link. A well-known example of this accommodation technique is optical soliton transmission. Optical solitons are return-to-zero signals with a certain pulse shape (and power) that can traverse a dispersive optical fibre without experiencing significant distortion. This is achieved by counterbalancing the dispersion-induced pulse-broadening with an equal amount of pulse-narrowing caused by self-phase modulation (SPM), which arises from nonlinear interactions of the optical signal with itself. In the absence of chromatic dispersion, the optical soliton pulses would collapse, and without SPM, they would become excessively broad.

In order to balance the pulse-broadening and pulse narrowing effects, each soliton pulse shall carry a well-defined amount of optical power, which depends on the fibre design (which determines the magnitude of the non-linear interactions) and the dispersion coefficient $D$. The larger $D$ is, the higher the optical power has to be. For practical applications, $D$ should be between 0,3 ps/nm-km and 1 ps/nm-km [32]. Soliton pulses have been generated in non-zero dispersion-shifted communication fibres and transmitted over very long distances. However, soliton transmission over dispersion-unshifted fibres is not practical in the 1 550-nm wavelength range, because of the large pulse powers required to generate sufficient SPM. Furthermore, soliton pulses are not well suited for DWDM transmission, because they introduce significant cross-phase modulation (XPM) between the multiplexed signals. Soliton transmission systems have not been widely deployed, because they cannot provide the same overall data capacity as conventional, quasi-linear communication systems.

### 6.7 Mid-span spectral inversion

Another technique for optical accommodation of dispersion is mid-span spectral inversion, which is also referred to as optical phase conjugation. Unlike dispersion-assisted transmission, this technique is agnostic to the bit rate and modulation format of the transmitted optical signals as well as to the fibre type. It does require, however, the addition of optical components in the middle of the fibre span (or link), to invert the optical spectrum of the transmitted signal in such a way that the red-shifted wavelengths of the input signal (i.e. the originally transmitted signal) become the blue-shifted wavelengths of the output signal (i.e. the spectrally inverted signal) and, conversely, the blue-shifted wavelengths of the input signal become the red-shifted wavelengths of the output signal (see Figure 8).

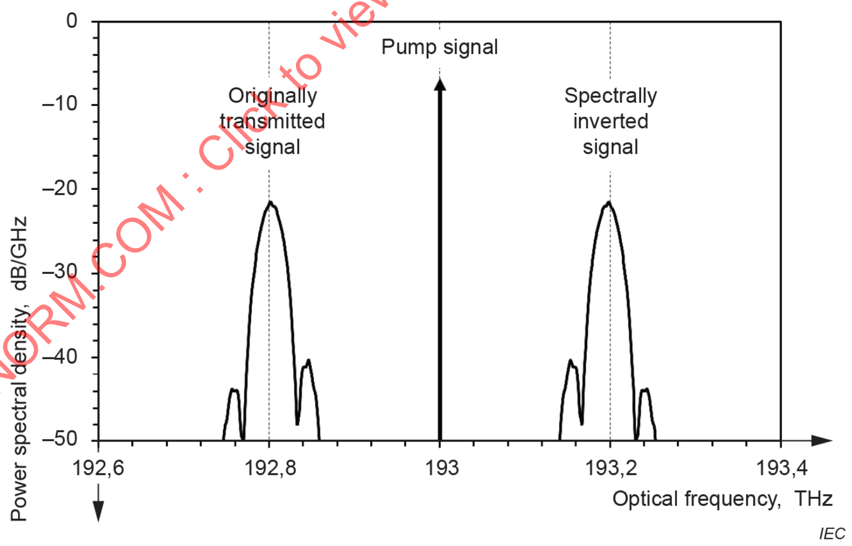



**Figure 8 – Spectral inversion of a modulated signal via four-wave mixing**

The result of this spectral inversion is that the dispersion-induced differential delays introduced in the red-shifted wavelengths during transmission through the first half of the fibre span are offset by opposite delays (i.e. advances) in the second half of the span, where they are transmitted as blue-shifted wavelengths. This effect is equivalent to a reversal of the sign of the dispersion coefficient in the second half of the span. Thus, if the dispersion coefficient is uniform along the fibre span, and the spectral inversion occurs exactly at mid-span, then there are no dispersion-induced waveform distortions in the received optical signal [33].

Spectral inversion of a modulated optical signal can be accomplished via four-wave mixing (FWM) or parametric optical amplification [34] in a nonlinear optical medium. In the case of FWM, the modulated optical signal is mixed with an unmodulated optical pump signal at a wavelength that is sufficiently offset from the centre wavelength of the modulated signal. This mixing creates a mirror image of the modulated optical spectrum on the other side of the pump wavelength, as shown schematically in Figure 8. In the most basic configuration, only a high-power pump laser and a nonlinear optical medium are needed, where the latter may be a compact semiconductor optical amplifier, a periodically poled lithium niobate waveguide, or a highly nonlinear fibre. An additional optical band-pass filter may be employed to block the pump signal and the original signal from entering the second half of the fibre span. It is usually not necessary to undo the spectral inversion at the receiver.

In practical applications, a more complex polarization-diversity arrangement is required to accommodate the polarization dependence of FWM and to allow spectral inversion of polarization-multiplexed signals [35]. Although it is possible to simultaneously invert the spectra of several closely-spaced DWDM signals in the same nonlinear medium [34] [35], spectral inversion in a fully loaded DWDM communication link requires de-multiplexing of the signals into several wavelength bands and parallel processing of these bands in separate inverters, because the spectrally inverted signals appear at different wavelengths. After inversion, the signals may be shifted back to their original wavelengths [36].

Thus, dispersion accommodation via mid-span spectral inversion is significantly more complex than broadband dispersion compensation via in-line PDCs. For this reason, it is not widely used in commercial communication systems. However, mid-span spectral inversion may be used in future systems to reduce the signal distortions caused by self-phase modulation [34] [35].



## 7 Passive dispersion compensator parameters

### 7.1 Compensated fibre length

Dispersion compensation modules based on PDCs are usually categorized by the amount of dispersion they can compensate. Since PDCs are designed to match the dispersion coefficient of a certain fibre type, their dispersion is often expressed in terms of the length of fibre whose dispersion they can compensate. This length is called "compensated fibre length" and specified in units of km.

### 7.2 Operating wavelength range

The operating wavelength range of a PDC is usually specified by minimal and maximal wavelengths (in nm), or sometimes by an optical wavelength band (e.g. C- or L-band). For PDCs with a single, continuous optical transmission band, such as DCF-based PDCs and certain FBG-based PDCs, all optical parameters (in terms of allowable minimum or maximum values) are to be satisfied within this wavelength range.

FBG-based PDCs with multi-channel passbands satisfy these parameters only within the specified passbands. The nominal centre frequencies of these passbands (or channels) are often characterized by the frequency spacing of the channels (e.g. 50 GHz or 100 GHz), which refers to the channel spacing and corresponding centre frequencies specified in ITU-T Recommendation G.694.1 for fixed DWDM channel grids [19]. The usable spectral width of the passbands is usually specified in GHz.

### 7.3 Chromatic dispersion

An important parameter of the PDC is the value of the total accumulated dispersion, which is specified either directly in units of ps/nm or indirectly by a nominal length of transmission fibre compensated for (i.e. the compensated fibre length). In the first case, the dispersion is specified by a nominal value at a given wavelength (e.g. 1 550 nm) and a range of maximal deviation from its nominal value (in %). In addition, the wavelength dependence of the dispersion may be characterized by nominal dispersion values at the two extremes of the operating wavelength range (e.g. in the first and last transmission bands). In case the dispersion is characterized by a compensated fibre length, the fibre type needs to be specified.

PDCs are usually available in discrete values, which may not exactly match the dispersion of a particular fibre span. Hence, if a PDC is designed for a specified length $L_c$ and installed in a fibre link of length $L$ with nominal dispersion coefficient $D$, the total uncompensated dispersion is $D \times (L - L_c)$. If $L = L_c$, the dispersion of the transmission fibre is nominally balanced by the dispersion of the PDC, otherwise it may be either under- or overcompensated.

Note that actual dispersion values of the PDC and the transmission fibre may deviate significantly from their nominal values, so that a fibre link may be under- or overcompensated even if $L = L_c$. This is particularly important for optically amplified long-haul communication links employing multiple in-line PDCs and for communication systems operating at high symbol rates, where the tolerance to uncompensated dispersion decreases rapidly with increasing symbol rate (see Table 2). In these cases, the use of nominal dispersion values may not be accurate enough to limit the uncompensated dispersion to sufficiently low values, so that it may become necessary to measure the accumulated dispersion of the entire fibre link, including the transmission fibre and PDCs. Such a measurement may also determine the actual dispersion slopes of the transmission fibre and the PDCs.

## 7.4 Dispersion slope

In DWDM systems with multi-channel operation, it is desirable to simultaneously compensate the dispersion in all wavelength channels, which requires that not only the dispersion at a particular wavelength but also the dispersion slope of the PDC are matched to the corresponding values of the transmission fibre. The dispersion slope of the PDC (in ps/nm$^2$) may be determined from the nominal dispersion values specified at the extremes of the wavelength range of operation.

Broadband dispersion compensation is achieved when the dispersion slope of the PDC is equal to $-S \times L$, where $S$ is the dispersion-slope coefficient of the transmission fibre, so that the dispersion of the PDC is equal to $-D \times L$ at all wavelengths. Note that the ratio of $D/S$ varies substantially between the various fibre types. Hence, slope compensating PDCs need to be designed for a specific fibre type and should be used only with this fibre type.

## 7.5 Insertion loss

Another important parameter is the optical insertion loss (IL) of the PDC, including external connectors, which is usually specified at a fixed wavelength (e.g. at 1 550 nm) and expressed in units of dB. The wavelength dependence of the IL is usually characterized by a separate parameter, the wavelength-dependent loss (see 7.6).

One can define a figure-of-merit in ps/nm-dB as the ratio of the magnitude of the dispersion in the PDC (in ps/nm) to its insertion loss (in dB). This ratio characterizes the efficacy of a PDC, since it calculates the amount of dispersion (or equivalently the length of transmission fibre) that can be compensated for each dB of additional insertion.

## 7.6 Wavelength-dependent loss

The wavelength dependence of the IL is characterized by the wavelength-dependent loss (WDL), which specifies the maximal variation of the insertion loss across the wavelength range of operation (in dB). This parameter is mostly used for PDCs with a single continuous passband (e.g. for DCFs).

For PDCs with multi-channel passbands, the wavelength dependence of the insertion loss is often specified by two different parameters, the passband flatness (in dB), which characterizes the maximal insertion loss ripple in all passbands, and the IL uniformity (also in dB), which characterizes the maximal insertion loss variations between the various passbands.

### 7.7 Phase ripple

Phase ripple is an important parameter for FBG-based PDCs, but usually negligible for DCF-based PDCs. It characterizes the magnitude of random or periodic group delay ripple introduced by the PDC (see Figure 4), which are caused by wavelength-dependent deviations from the desired dispersion $-D(\lambda) \times L$. Depending on their magnitude and wavelength dependence, these deviations can cause significant transmission penalties in a communication system. It has been found that the magnitude of the optical phase ripple resulting from the group delay ripple is a better measure of these penalties than the magnitude of the group delay ripple [20]. The phase ripple $\delta\phi(\lambda)$ is the difference between the optical phase variations $\Delta\phi_{CD}(\lambda)$ associated with the desired dispersion $-D(\lambda) \times L$ (see Equation (2)) and the actual phase variations $\Delta\phi_{PDC}(\lambda)$ introduced in the PDC, i.e. $\delta\phi(\lambda) = \Delta\phi_{CD}(\lambda) - \Delta\phi_{PDC}(\lambda)$. Phase ripple is usually specified by the standard deviation of $\delta\phi(\lambda)$, in units of radians.

### 7.8 Reflectance

In optical components, discrete and continuous reflections, both single and multiple, may occur. The reflected signals can interfere with the transmitted signals (e.g. via double reflections) and lead to significant waveform distortions at the receiver. In a PDC, there are two potential types of reflections. Discrete reflections, for example, may occur at splices between the DCF (or FBG) and the fibre connectors leading to the input and output ports, which may employ fused tapers to match the mode field diameters of different fibres. In addition, continuous reflections may result from Rayleigh scattering in the dispersion-compensating element. Rayleigh scattering in DCFs is generally larger than in transmission fibres due to the smaller mode field diameter. FBGs are usually operated in a reflective mode, but may also introduce continuous reflections.

### 7.9 Polarization-mode dispersion

Polarization-mode dispersion (PMD) arises from the combined effects of optical birefringence and polarization mode coupling in transmission fibres, PDCs, optical amplifiers, and other optical components. To first order, PMD introduces a differential group delay (DGD) between two orthogonally polarized signal components, called the principal states of polarization (PSPs), which may cause significant pulse broadening or frequency roll-off. In long fibre links, the DGD and the orientation of the PSPs usually vary with wavelength and may even fluctuate randomly with time. Hence PMD is more statistical in nature than CD. However, it is possible to characterize the magnitude of the DGD variations by a statistical average (i.e. by an expectation value). This average DGD, in units of picoseconds (ps), is determined from a sufficiently large ensemble of DGD values that are measured either simultaneously at different wavelengths or, alternatively, at different times at a fixed wavelength. Two different definitions are in use to characterize the average DGD:

1) mean DGD, which is the linear average of the measured DGD values;
2) RMS DGD, which is the root-mean-square average of the DGD values.

Usually, the RMS DGD is significantly larger than the mean DGD (about 8,5 % for Maxwellian distributed DGDs).

Note that the term PMD frequently is used as a parameter to specify the average DGD of a component, instead of mean or RMS DGD. Since the parameter PMD is interchangeably used for mean and RMS DGD, it often remains unclear whether the specified value (in ps) represents the mean DGD or the RMS DGD.

In a long fibre optic link with multiple in-line PDCs, each having a mean DGD of $\tau_i$, the overall total mean DGD may be estimated as:

$$\tau_{tot} = \sqrt{\tau_1{}^2 + \tau_2{}^2 + \tau_3{}^2 + \ldots + \tau_f{}^2} \quad (6)$$

where

$\tau_f$ is the mean DGD of the transmission fibre.

In general, the mean DGD of the individual PDCs should be much smaller than the mean DGD of the transmission fibre.

System design methodologies taking into account the stochastic nature of fibre PMD and the PMD of other components, including PDCs, are described in IEC TR 61282-3.

### 7.10 Polarization-dependent loss

The insertion loss of optical components often varies with the state of polarization of the input signal. These variations are characterized by the polarization-dependent loss (PDL), usually specified in dB, which is the difference between the highest and lowest IL (in dB) that is measured when the input polarization to the component is varied over all possible states.

In a simple optical component, the PDL and the polarization states yielding the highest and lowest insertion loss are usually fixed and stable in time, although the PDL may change with wavelength. In more complex components, especially those comprising multiple elements that are connected by optical fibres or other birefringent waveguides, the amount of PDL and the polarization states with highest and lowest IL may change with wavelength and time. In long fibre links containing a large number of in-line components with PDL (like PDCs), the overall PDL usually fluctuates randomly between the largest possible value (given by the sum of all PDLs in dB) and the smallest possible value. Therefore, the PDL of the individual components should be as small as possible to maintain stability of optical power and OSNR at the receiver, thereby minimizing the transmission penalty.

### 7.11 Optical nonlinearity

As discussed in IEC TR 61282-4, the optical power levels in a fibre link can be large enough to cause significant distortion of the transmitted signals through nonlinear interactions, such as SPM, XPM or FWM. These nonlinear interactions can occur in the transmission fibre as well as in in-line PDCs, especially in DCF-based PDCs. DCFs tend to have fibre cores with substantially smaller effective areas and correspondingly higher optical power densities than conventional transmission fibres. To avoid excessive signal distortion in in-line DCFs, they should typically be placed before optical amplifiers (where the power levels are lowest) or, if possible, after the first stage of a multi-stage amplifier (where the power levels are still relatively low) to avoid excessive degradations of the optical signal-to-noise ratio (OSNR).

DCF-based PDCs may specify the effective area of the DCF (in $\mu m^2$) as well as its nonlinear coefficient (in $W^{-1}km^{-1}$). Because of their much shorter length, optical nonlinearities usually are not a problem for FBG-based PDCs.

### 7.12 Latency

With increasing bit rates and transmission distances, latency is becoming an important parameter for high-speed optical communication systems. Latency is the amount of time it takes for a bit or symbol to traverse an optical communication system from one end to the other. It includes the transit time through the fibre as well as the time needed for electronic signal processing at the transmitter and receiver. Thus, latency may be affected by the type of PDCs used in the fibre link. DCF-based PDCs significantly extend the optical path length of a fibre link and thereby increase the transit time for the optical signals. For example, one needs about 100 km of DCF to compensate for the chromatic dispersion of a 1 000-km long span of B-652 fibre, thus adding about 500 μs to the latency of the link. In a 100 Gbit/s communication system, this time corresponds to a delay by 50 million bits. FBG-based PDCs, on the other hand, have much shorter optical path lengths than DCF-based PDCs and, hence, add negligible additional latency to the link. Similarly, there is negligible increase in latency when the entire link dispersion is accommodated electronically in the transmitter or receiver.

# 8 Passive dispersion compensator applications

## 8.1 Unamplified fibre spans

Depending on fibre type and length, unamplified fibre spans may need PDCs when operating at bit rates of 10 Gbit/s and above. When no optical amplifiers are used, the PDC may be placed anywhere along the link; however, they are often placed at the receiver (Rx) to reduce non-linear effects, as shown in Figure 9. Generally, DCF-based PDCs are directionally invariant and can be used in bidirectional systems. In contrast, FBG-based PDCs are usually unidirectional devices, which cannot be employed in bidirectional systems.

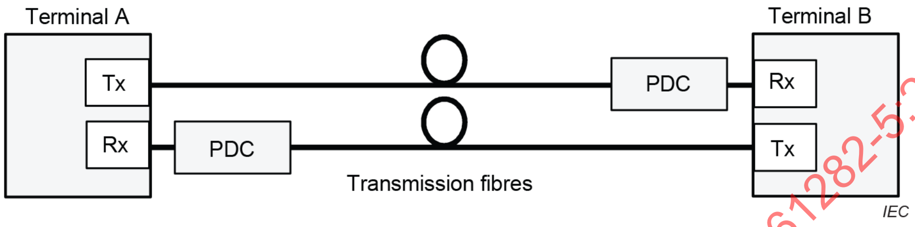



**Figure 9 – Passive dispersion compensators placed at the receiver**

For long fibre spans it may be necessary to increase the launched signal power at the transmitter (Tx) with the help of an optical booster amplifier, as shown in Figure 10. In addition, an optical pre-amplifier may be used at the other end of the fibre span to increase the power of the received signal, as shown in Figure 11.

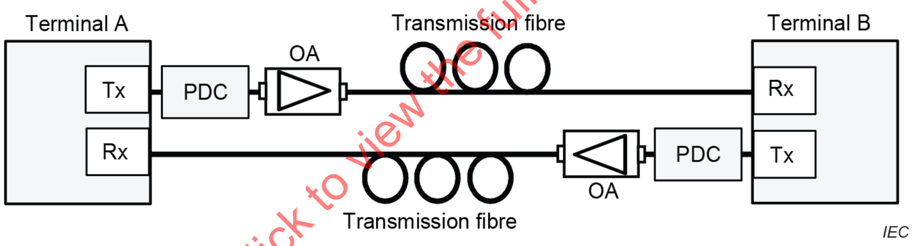



**Figure 10– PDCs placed before optical booster amplifiers at the transmitter**

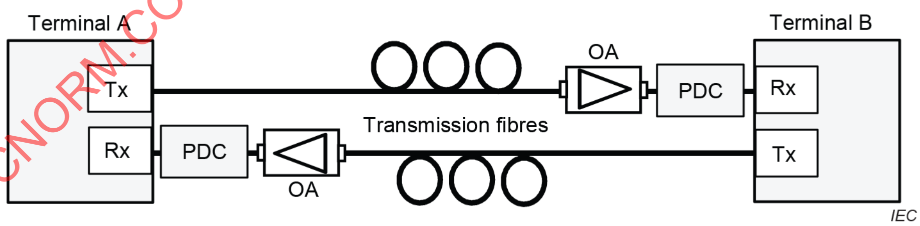



**Figure 11 – PDCs placed after pre-amplifiers at the receiver**

PDCs should generally not be placed immediately after a booster-amplifier, but rather before it, to avoid non-linear effects that can occur at high power levels. However, PDCs may be placed directly after an optical pre-amplifier at the receiver because its output power level is usually low enough to avoid non-linear effects.

## 8.2 Fibre links with in-line optical amplifiers

In long-haul communication links with in-line optical amplification, PDCs are often co-located with the optical amplifiers (OAs) to limit the accumulation of dispersion along the fibre link, as discussed in 6.2. If the OAs are single-stage amplifiers, the PDCs should be inserted just before the OAs, as shown in the upper diagram of Figure 12, to avoid non-linear effects in the PDCs.