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ITU-T G.652 (08/2024)

SERIES G: Transmission systems and media, digital systems and networks

Transmission media and optical systems characteristics – Optical fibre cables

Characteristics of a single-mode optical fibre and cable

ITU-T G-SERIES RECOMMENDATIONS

Transmission systems and media, digital systems and networks

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Recommendation ITU-T G.652

Characteristics of a single-mode optical fibre and cable

Summary

Recommendation ITU-T G.652 describes the geometrical, mechanical and transmission attributes of a single-mode optical fibre and cable which has zero-dispersion wavelength around 1310 nm. The ITU-T G.652 fibre was originally optimized for use in the 1310 nm wavelength region but can also be used in the 1550 nm region. This is the latest revision of a Recommendation that was first created in 1984 and deals with some relatively minor modifications.

In this revision, an example guideline for the statistical chromatic dispersion coefficient in a link with a number of concatenated cable pieces of *M* equal 1 to 16 is provided in Appendix I, clause I.6.

History*

Edition	Recommendation	Approval	Study Group	Unique ID
1.0	ITU-T G.652	1984-10-19		11.1002/1000/4091
2.0	ITU-T G.652	1988-11-25		11.1002/1000/882
3.0	ITU-T G.652	1993-03-12	15	11.1002/1000/883
4.0	ITU-T G.652	1997-04-08	15	11.1002/1000/4018
5.0	ITU-T G.652	2000-10-06	15	11.1002/1000/5183
6.0	ITU-T G.652	2003-03-16	15	11.1002/1000/6261
7.0	ITU-T G.652	2005-06-29	15	11.1002/1000/8522
8.0	ITU-T G.652	2009-11-13	15	11.1002/1000/10389
9.0	ITU-T G.652	2016-11-13	15	11.1002/1000/13076
10.0	ITU-T G.652	2024-08-29	15	11.1002/1000/16060

Keywords

Dispersion un-shifted optical fibre, optical fibre and cable, single-mode optical fibre.

* To access the Recommendation, type the URL https://handle.itu.int/ in the address field of your web browser, followed by the Recommendation's unique ID.

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Change log

Overview of the changes introduced in this Recommendation since it was first approved in 1984.

Edition	Recommendation	Changes
1.0	ITU-T G.652 (1984)	
2.0	ITU-T G.652 (1988)	
3.0	ITU-T G.652 (1993)	
4.0	ITU-T G.652 (1997)	
5.0	ITU-T G.652 (2000)	This revision includes the addition of tables for different levels of system support.
6.0	ITU-T G.652 (2003)	This revision clarified the nomenclature for the different categories or fibre. Also, in accordance with the agreement on spectral band description, the upper limit of the L-band is changed from 16XX to 1625 nm. The attenuation characteristics for reduced water peak categories, (G.652.C and G.652.D) are generalized to a broad region from a single wavelength. PMD requirements are added for all categories and two categories have reduced limits (compared to 0.5 ps/$\sqrt{\text{km}}$). For the macrobending test, mandrel diameter is reduced to 30 mm radius. As seen above, this Recommendation has evolved considerably over the years; therefore, the reader is warned to consider the appropriate version to determine the characteristics of already deployed product, taking into account the year of production. In fact, products are expected to comply with the Recommendation that was in force at the time of their manufacture, but may not fully comply with subsequent versions of the Recommendation.
7.0	ITU-T G.652 (2005)	Support of G.695 applications is noted. A clarification of the method of fitting chromatic dispersion coefficient values and their use is provided in 5.10, along with some text on use of the statistics of chromatic dispersion for system design. A clarification of the relationship of the PMD_Q of uncabled fibre to cabled fibre is provided in 6.2. In the tables of requirements: The uncabled fibre PMD line item is removed from the tables and the note on the requirement for uncabled fibre PMD is modified. The tolerance of MFD at 1310 nm is reduced. The maximum dispersion slope at the zero dispersion wavelength is reduced. The maximum concentricity error is reduced. The maximum macrobending loss is reduced. The wording for the water peak requirement in Tables 3 and 4 are modified to reflect a reference to the specification over the range vs the specification at 1310 nm.
8.0	ITU-T G.652 (2009)	Add IEC-60794-2-11 as an informative reference in clause 2.2. Editorial correction at start of clause 6.2 (PMD). New note has been introduced in Table 1 – 4 allowing higher maximum cabled attenuation (1.0 dB/km) for short indoor cables. Modification in Tables 3 and 4 to the cabled attenuation at 1383 nm (max. 0.40 dB/km). New text has been introduced in Tables 3 and 4 concerning hydrogen ageing (Note 3).
9.0	ITU-T G.652 (2016)	Tables 1 and 3 of edition 8 have not been changed. These tables are not included in this version of Recommendation ITU-T G.652, but are in the 2009 edition. The tables in this edition have been renumbered. Tables 1 and 2 of this edition 9 correspond respectively to Tables 2 and 4 of edition 8.

		New clause 5 "Conventions" has been added. Following clause numbers have been renumbered. Chromatic dispersion specification for G.652.D fibres has been changed into boundary line specification. In clause 6.10 the text concerning chromatic dispersion for G.652.D fibres has been modified. In clause 7.2 (PMD) a note has been added about usability of high PMD fibre and cable for systems with less stringent PMD requirements. In clause 8 only Table 1 (G.652.B) and Table 2 (G.652.D) are indicated. Here also a reference to IEC fibre designations is mentioned. In Table 1 (G.652.B) and Table 2 (G.652.D) Note 1 has been extended with text concerning attenuation coefficient at a wavelength longer than 1625 nm. In Table 1 (G.652.B) new Note 3 and Table 2 (G.652.D) new Note 5 describe usability of high PMD fibre and cable for system with less stringent PMD requirements. In Table 2 (G.652.D) the nominal mode field diameter upper range has been reduced. In Table 2 (G.652.D) the mode field diameter tolerance has been tightened. In Table 2 (G.652.D) the cladding diameter tolerance has been tightened. In Table 2 (G.652.D) new specification has been introduced for chromatic dispersion. In Table 2 (G.652.D) text has been added and renewed concerning attenuation coefficient at 1383 nm. In Table 2 (G.652.D) the attenuation specifications have been edited to two decimal places. Added in Appendix I a new clause I.6 "An example of statistical methodology". New Appendix II has been added highlighting the data collection on maximum and minimum chromatic dispersion over wavelength range 1270 nm to 1625 nm for the boundary line specification of G.652.D fibres.
10.0	ITU-T G.652 (2024)	New clauses "I.6.2 Statistical design example for O-band chromatic dispersion in a link" and "I.6.3 Influence of number of concatenated cable pieces M on PMDQ and DGD" were included in the Appendix I. Description for the cut-off wavelength in clause 6.5 was amended to be consistent with the Recommendation G.654 (Ed. 12).

Recommendation ITU-T G.652

Characteristics of a single-mode optical fibre and cable

1 Scope

This Recommendation describes a single-mode optical fibre and cable which has zero-dispersion wavelength around 1310 nm and can be used in the 1310 nm and 1550 nm regions. Both analogue and digital transmission can be used with this fibre.

The geometrical, optical, transmission and mechanical parameters are described below in three categories of attributes:

- fibre attributes are those attributes that are retained throughout cabling and installation;
- cable attributes that are recommended for cables as delivered;
- link attributes that are characteristic of concatenated cables, describing estimation methods of system interface parameters based on measurements, modelling or other considerations. Information for link attributes, system design, and example statistical link design are in Appendix I.

This Recommendation and the different performance categories found in the tables of clause 8 are intended to support the following related system Recommendations:

Category	Recommendations
Characteristics of optical systems	[b-ITU-T G.691], [b-ITU-T G.692], [b-ITU-T G.693], [b-ITU-T G.695], [b-ITU-T G.696.1], [b-ITU-T G.698.1], [b-ITU-T G.698.2], [b-ITU-T G.698.3], [b-ITU-T G.698.4], [b-ITU-T G.698.5], [b-ITU-T G.698.6]
Optical fibre submarine cable systems	[b-ITU-T G.973], [b-ITU-T G.973.1], [b-ITU-T G.973.2], [b-ITU-T G.977.1]
Digital line systems	[b-ITU-T G.957], [b-ITU-T G.959.1]
Optical line systems for local and access networks	[b-ITU-T G.983.1], [b-ITU-T G.984.2], [b-ITU-T G.985], [b-ITU-T G.986], [b-ITU-T G.987.2], [b-ITU-T G.989.2]

NOTE – Depending on the length of the links, dispersion accommodation can be necessary for some [b-ITU-T G.691], [b-ITU-T G.692] or [b-ITU-T G.959.1] application codes.

The meaning of the terms used in this Recommendation and the guidelines to be followed in the measurement to verify the various characteristics are given in [ITU-T G.650.1] and [ITU-T G.650.2]. The characteristics of this fibre, including the definitions of the relevant parameters, their test methods and relevant values, will be refined as studies and experience progress.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T G.650.1] Recommendation ITU-T G.650.1 (2024), *Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable*.

[ITU-T G.650.2] Recommendation ITU-T G.650.2 (2015), *Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable*.

[IEC 60793-2-50] IEC 60793-2-50:2018 Ed. 6.0, *Optical fibres – Part 2-50: Product specifications – Sectional specification for class B single mode fibres*.

[ISO 80000-1] ISO 80000-1:2022, *Quantities and units – Part 1: General.*

3 Definitions

3.1 Terms defined elsewhere

For the purposes of this Recommendation, the definitions given in [ITU-T G.650.1] and [ITU-T G.650.2] apply.

3.2 Terms defined in this Recommendation

None.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

A_{eff} Effective Area

DGD Differential Group Delay

DWDM Dense Wavelength Division Multiplexing

LDV Link Design Value

PMD Polarization Mode Dispersion

PMD_Q Statistical parameter for link PMD

SDH Synchronous Digital Hierarchy

WDM Wavelength Division Multiplexing

5 Conventions

Values shall be rounded to the number of digits given in the tables of recommended values before conformance is evaluated. The conventional rounding rule of "rounding half away from zero" is used, which is described in Annex B, Rule B of [ISO 80000-1]. Only the first digit beyond the number of significant digits is used in determining the rounding.

6 Fibre attributes

Only those characteristics of the fibre providing a minimum essential design framework for fibre manufacture are recommended in this clause. Ranges or limits on values are presented in the tables of clause 8. Of these, cable manufacture or installation may significantly affect the cabled fibre cut-off wavelength and PMD. Otherwise, the recommended characteristics will apply equally to individual fibres, fibres incorporated into a cable wound on a drum and fibres in an installed cable.

6.1 Mode field diameter

Both a nominal value and tolerance about that nominal value shall be specified at 1310 nm. The nominal value that is specified shall be within the range found in clause 8. The specified tolerance shall not exceed the value in clause 8. The deviation from nominal shall not exceed the specified tolerance.

6.2 Cladding diameter

The recommended nominal value of the cladding diameter is 125 µm. A tolerance is also specified and shall not exceed the value in clause 8. The cladding deviation from nominal shall not exceed the specified tolerance.

6.3 Core concentricity error

The core concentricity error shall not exceed the value specified in clause 8.

6.4 Non-circularity

6.4.1 Mode field non-circularity

In practice, the mode field non-circularity of fibres having nominally circular mode fields is found to be sufficiently low that propagation and jointing are not affected. It is, therefore, not considered necessary to recommend a particular value for the mode field non-circularity. It is not normally necessary to measure the mode field non-circularity for acceptance purposes.

6.4.2 Cladding non-circularity

The cladding non-circularity shall not exceed the value found in clause 8.

6.5 Cut-off wavelength

Two useful types of cut-off wavelength can be distinguished:

a) cable cut-off wavelength λ_{cc};

b) fibre cut-off wavelength λ_c.

NOTE 1 – For some specific submarine cable applications, other cable cut-off wavelength values may be required.

The correlation of the measured values of λ_c and λ_{cc} depends on the specific fibre and cable design and the test conditions. While in general $\lambda_{cc} < \lambda_c$, a general quantitative relationship cannot be easily established. The importance of ensuring single-mode transmission in the minimum cable length between joints at the minimum operating wavelength is paramount. This may be performed by recommending the maximum cable cut-off wavelength λ_{cc} of a cabled single-mode fibre to be 1260 nm.

NOTE 2 – Cut-off wavelength intrinsically contains length or bending dependence. In the case of a unique deployment condition expected in a link (e.g., a piece length becomes shorter than 22 m without specific bending), cut-off wavelength under the expected condition should be ensured to have negligible influence on system performance. The cable cut-off wavelength, λ_{cc}, shall be less than the maximum specified in clause 8.

6.6 Macrobending loss

Macrobending loss varies with wavelength, bend radius and number of turns about a mandrel with a specified radius. Macrobending loss shall not exceed the maximum given in clause 8 for the specified wavelength(s), bend radius and number of turns.

NOTE 1 – A qualification test may be sufficient to ensure that this requirement is being met.

NOTE 2 – The recommended number of turns corresponds to the approximate number of turns deployed in all splice cases of a typical repeater span. The recommended radius is equivalent to the minimum bend-radius widely accepted for long-term deployment of fibres in practical systems installations to avoid static-fatigue failure.

NOTE 3 – If, for practical reasons, fewer than the recommended number of turns is chosen to be implemented, it is suggested that not less than 40 turns, and that a proportionately smaller loss increase be required.

NOTE 4 – The macrobending loss recommendation relates to the deployment of fibres in practical single-mode fibre installations. The influence of the stranding-related bending radii of cabled single-mode fibres on the loss performance is included in the loss specification of the cabled fibre.

NOTE 5 – In the event that routine tests are required, a smaller diameter loop with one or several turns can be used instead of the recommended test, for accuracy and measurement ease. In this case, the loop diameter, number of turns and the maximum permissible bend loss for the several-turn test should be chosen so as to correlate with the recommended test and allowed loss.

6.7 Material properties of the fibre

6.7.1 Fibre materials

The substances of which the fibres are made should be indicated.

NOTE – Care may be needed in fusion splicing fibres of different substances. Provisional results indicate that adequate splice loss and strength can be achieved when splicing different high-silica fibres.

6.7.2 Protective materials

The physical and chemical properties of the material used for the fibre primary coating and the best way of removing it (if necessary) should be indicated. In the case of single-jacketed fibre, similar indications shall be given.

6.7.3 Proof stress level

The specified proof stress σ_p shall not be less than the minimum specified in clause 8.

NOTE – The definitions of the mechanical parameters are contained in clauses 3.2 and 6.6 of [ITU-T G.650.1].

6.8 Refractive index profile

The refractive index profile of the fibre does not generally need to be known.

6.9 Longitudinal uniformity of chromatic dispersion

Under study.

NOTE – At a particular wavelength, the local absolute value of the chromatic dispersion coefficient can vary away from the value measured on a long length. If the value decreases to a small value at a wavelength that is close to an operating wavelength in a wavelength division multiplexing (WDM) system, four-wave mixing can induce the propagation of power at other wavelengths including, but not limited to, other operating wavelengths. The magnitude of the four-wave mixing power is a function of the absolute value of the chromatic dispersion coefficient, the chromatic dispersion slope, the operating wavelengths, the optical power, and the distance over which four-wave mixing occurs.

For dense wavelength division multiplexing (DWDM) operations in the 1550 nm region, the chromatic dispersion of ITU-T G.652 fibres is large enough to avoid four-wave mixing. Chromatic dispersion uniformity is, therefore, not a functional issue.

6.10 Chromatic dispersion

The measured group delay or chromatic dispersion coefficient versus wavelength shall be fitted by suitable equations as described in Annex A of [ITU-T G.650.1] (see clause 6.5 of [ITU-T G.650.1] for guidance on the interpolation of dispersion values to unmeasured wavelengths).

For sub-category G.652.B fibre the chromatic dispersion coefficient, $D(\lambda)$, is specified by putting limits on the parameters of a chromatic dispersion curve that is a function of wavelength in the 1310 nm region. The chromatic dispersion coefficient limit for any wavelength, λ, is calculated with the minimum zero-dispersion wavelength, λ_{0min}, the maximum zero-dispersion wavelength, λ_{0max}, and the maximum zero-dispersion slope, S_{0max}, according to:

$$D(\lambda) \le \frac{\lambda S_{0\max}}{4}\left[1-\left(\frac{\lambda_{0\min}}{\lambda}\right)^4\right] \qquad (6\text{-}1)$$

The values of $\lambda_{0\min}$, $\lambda_{0\max}$ and $S_{0\max}$ shall be within the limits indicated in Table 1 (clause 8).

For sub-category G.652.D fibre the chromatic dispersion parameters indicated in Table 2 (clause 8) are specified in order to bind the chromatic dispersion values from 1260 nm to 1625 nm. This allows more accurate system design in which dispersion compensating schemes are incorporated. When specifying the chromatic dispersion coefficient parameters of G.652.D fibres only by the three-term Sellmeier coefficients in the 1310 nm region, the dispersion coefficient may not be sufficiently accurate when extrapolated to the 1550 nm region. In order to bind the minimum/maximum chromatic dispersion coefficients of G.652.D fibres, combining the first derivative of the three-term Sellmeier fitting on group delay from 1260 nm to 1460 nm and linear fitting on chromatic dispersion (i.e., the first derivative of the quadratic fitting on group delay) from 1460 nm to 1625 nm is appropriate.

From 1260 nm to 1460 nm, chromatic dispersion coefficient $D(\lambda)$ at wavelength λ is bound by the following three inequalities:

$$\frac{\lambda S_{0\max}}{4}\left[1-\left(\frac{\lambda_{0\max}}{\lambda}\right)^4\right] \le D(\lambda) \le \frac{\lambda S_{0\min}}{4}\left[1-\left(\frac{\lambda_{0\min}}{\lambda}\right)^4\right] \qquad (\lambda \le \lambda_{0\min}), \qquad (6\text{-}2a)$$

$$\frac{\lambda S_{0\max}}{4}\left[1-\left(\frac{\lambda_{0\max}}{\lambda}\right)^4\right] \le D(\lambda) \le \frac{\lambda S_{0\max}}{4}\left[1-\left(\frac{\lambda_{0\min}}{\lambda}\right)^4\right] \qquad (\lambda_{0\min} \le \lambda \le \lambda_{0\max}), \qquad (6\text{-}2b)$$

$$\frac{\lambda S_{0\min}}{4}\left[1-\left(\frac{\lambda_{0\max}}{\lambda}\right)^4\right] \le D(\lambda) \le \frac{\lambda S_{0\max}}{4}\left[1-\left(\frac{\lambda_{0\min}}{\lambda}\right)^4\right] \qquad (\lambda_{0\max} \le \lambda). \qquad (6\text{-}2c)$$

The minimum chromatic dispersion slope, $S_{0\min}$, has been added in order to bind both the minimum and maximum chromatic dispersion coefficients.

From 1460 nm to 1625 nm, chromatic dispersion coefficient $D(\lambda)$ at wavelength λ is bound by the following inequality:

$$8.625 + 0.052(\lambda - 1460) \le D(\lambda) \le 12.472 + 0.068(\lambda - 1460) \qquad (6\text{-}3)$$

A survey on G.652.D products was conducted to determine the chromatic dispersion parameter specifications and consequences in terms of the dispersion envelope. The results are summarized in Appendix II of this Recommendation.

NOTE – It is not necessary to measure the chromatic dispersion coefficient of single-mode fibre on a routine basis.

7 Cable attributes

Since the geometrical and optical characteristics of fibres given in clause 6 are barely affected by the cabling process, this clause gives recommendations mainly relevant to transmission characteristics of cabled factory lengths.

Environmental and test conditions are paramount and are described in the guidelines for test methods.

7.1 Attenuation coefficient

The attenuation coefficient is specified with a maximum value at one or more wavelengths in both the 1310 nm and 1550 nm regions. The optical fibre cable attenuation coefficient values shall not exceed the values found in clause 8.

NOTE – The attenuation coefficient may be calculated across a spectrum of wavelengths, based on measurements at a few (3 to 4) predictor wavelengths. This procedure is described in clause 6.4.4 of [ITU-T G.650.1] and an example is given in Appendix III of [ITU-T G.650.1].

7.2 Polarization mode dispersion coefficient

Cabled fibre polarization mode dispersion shall be specified on a statistical basis, not on an individual fibre basis. The requirements pertain only to the aspect of the link calculated from cable information. The metrics of the statistical specification are found below. Methods of calculations are found in [b-IEC/TR 61282-3], and are summarized in Appendix IV of [ITU-T G.650.2].

The manufacturer shall supply a PMD link design value, PMD_Q, which serves as a statistical upper bound for the PMD coefficient of the concatenated optical fibre cables within a defined possible link of M cable sections. The upper bound is defined in terms of a small probability level, Q, which is the probability that a concatenated PMD coefficient value exceeds PMD_Q. For the values of M and Q given in clause 8, the value of PMD_Q shall not exceed the maximum PMD coefficient specified in clause 8.

Measurements and specifications on uncabled fibre are necessary, but not sufficient to ensure the cabled fibre specification. The maximum link design value specified on uncabled fibre shall be less than or equal to that specified for the cabled fibre. The ratio of PMD values for uncabled fibre to cabled fibre depends on the details of the cable construction and processing, as well as on the mode coupling condition of the uncabled fibre. [ITU-T G.650.2] recommends a low mode coupling deployment requiring a low-tension wrap on a large diameter spool for uncabled fibre PMD measurements.

The limits on the distribution of PMD coefficient values can be interpreted as being nearly equivalent to limits on the statistical variation of the differential group delay (DGD), that varies randomly with time and wavelength. When the PMD coefficient distribution is specified for optical fibre cable, equivalent limits on the variation of DGD can be determined. The metrics and values for link DGD distribution limits are found in Appendix I.

NOTE 1 – PMD_Q specification would be required only where cables are employed for systems that have the specification of the max DGD, i.e., for example, PMD_Q specification would not be applied to systems recommended in [b-ITU-T G.957].

NOTE 2 – PMD_Q should be calculated for various types of cables, and they should usually be calculated using sampled PMD values. The samples would be taken from cables of similar construction.

NOTE 3 – The PMD_Q specification should not be applied to short cables such as jumper cables, indoor cables and drop cables.

NOTE 4 – Optical fibre and cable with higher PMD coefficient can be used for systems with less stringent PMD requirements (e.g., systems with short link lengths or those with high PMD tolerance).

8 Tables of recommended values

The following tables summarize the recommended values for a number of categories of fibres that satisfy the objectives of this Recommendation. These categories are largely distinguished on the basis of attenuation requirement at 1383 nm. The historical relationship between maximum PMD_Q value and supporting bit rate can be found in Appendix I.

Table 1, ITU-T G.652.B attributes, contains recommended attributes and values needed to support higher bit rate applications, up to STM-64, such as some in [b-ITU-T G.691] and [b-ITU-T G.692], STM-256 for some applications in [b-ITU-T G.693] and [b-ITU-T G.959.1]. Depending on the application, chromatic dispersion accommodation may be necessary.

Table 2, ITU-T G.652.D attributes, is similar to ITU-T G.652.B, but allows transmissions in portions of an extended wavelength range from 1260 nm to 1625 nm.

Class reference table between IEC fibre category and ITU-T G.65x fibre types is given in Table V.1 in Appendix V of [b-ITU-T G-Sup.40].

Table 1 – ITU-T G.652.B attributes

Fibre attributes			
Attribute	**Detail**	**Value**	**Unit**
Mode field diameter	Wavelength	1310	nm
	Range of nominal values	8.6-9.5	µm
	Tolerance	±0.6	µm
Cladding diameter	Nominal	125.0	µm
	Tolerance	±1	µm
Core concentricity error	Maximum	0.6	µm
Cladding non-circularity	Maximum	1.0	%
Cable cut-off wavelength	Maximum	1260	nm
Macrobending loss	Radius	30	mm
	Number of turns	100	
	Maximum at 1625 nm	0.1	dB
Proof stress	Minimum	0.69	GPa
Chromatic dispersion parameter	λ_{0min}	1 300	nm
	λ_{0max}	1 324	nm
	S_{0max}	0.092	ps/(nm^2 × km)
Cable attributes			
Attribute	**Detail**	**Value**	**Unit**
Attenuation coefficient (Note 1)	Maximum at 1310 nm	0.4	dB/km
	Maximum at 1550 nm	0.35	dB/km
	Maximum at 1625 nm	0.4	dB/km
PMD coefficient (Note 2, 3)	M	20	cables
	Q	0.01	%
	Maximum PMD_Q	0.20	ps/$\sqrt{km}$

NOTE 1 – The attenuation coefficient values listed in this table should not be applied to short cables such as jumper cables, indoor cables and drop cables. For example, [b-IEC 60794-2-11] specifies the attenuation coefficient of indoor cable as 1.0 dB/km or less at both 1310 and 1550 nm. Attenuation coefficient at a wavelength longer than 1625 nm (for monitoring purpose) is not well known. In general, the attenuation increases as the wavelength increases, and it may show steep wavelength dependence due to both macro- and microbending losses.

NOTE 2 – According to clause 7.2, a maximum PMD_Q value on uncabled fibre is specified in order to support the primary requirement on cable PMD_Q.

NOTE 3 – Optical fibre cables with higher PMD coefficient can be used for systems with less stringent PMD requirements.

Table 2 – ITU-T G.652.D attributes

Fibre attributes			
Attribute	**Detail**	**Value**	**Unit**
Mode field diameter	Wavelength	1310	nm
	Range of nominal values	8.6-9.2	µm
	Tolerance	±0.4	µm
Cladding diameter	Nominal	125.0	µm
	Tolerance	±0.7	µm
Core concentricity error	Maximum	0.6	µm
Cladding noncircularity	Maximum	1.0	%
Cable cut-off wavelength	Maximum	1260	nm
Macrobending loss	Radius	30	mm
	Number of turns	100	
	Maximum at 1625 nm	0.1	dB
Proof stress	Minimum	0.69	GPa
Chromatic dispersion parameter 3-term Sellmeier fitting (1260 nm to 1460 nm)	λ_{0min}	1 300	nm
	λ_{0max}	1 324	nm
	S_{0min}	0.073	ps/(nm^2 × km)
	S_{0max}	0.092	ps/(nm^2 × km)
Linear fitting (1460 nm to 1625 nm)	Minimum at 1550 nm	13.3	ps/(nm × km)
	Maximum at 1550 nm	18.6	ps/(nm × km)
	Minimum at 1625 nm	17.2	ps/(nm × km)
	Maximum at 1625 nm	23.7	ps/(nm × km)
Cable attributes			
Attribute	**Detail**	**Value**	**Unit**
Attenuation coefficient (Note 1)	Maximum from 1310 nm to 1625 nm (Note 2)	0.40	dB/km
	Maximum at 1383 nm ±3 nm after hydrogen ageing (Note 3)	0.40	dB/km
	Maximum at 1530-1565 nm	0.30	dB/km
PMD coefficient (Note 4, 5)	M	20	cables
	Q	0.01	%
	Maximum PMD_Q	0.20	ps/$\sqrt{km}$

NOTE 1 – The attenuation coefficient values listed in this table should not be applied to short cables such as jumper cables, indoor cables and drop cables. For example, [b-IEC 60794-2-11] specifies the attenuation coefficient of indoor cable as 1.0 dB/km or less at both 1310 and 1550 nm. Attenuation coefficient at a wavelength longer than 1625 nm (for monitoring purpose) is not well known, but typically increases as the wavelength increases, and it may show steep wavelength dependence due to both macro and microbending losses.

NOTE 2 – This wavelength region can be extended to 1260 nm by adding 0.07 dB/km induced Rayleigh scattering loss to the attenuation value at 1310 nm.

NOTE 3 – The hydrogen ageing is a type test that shall be done to a set of sampled fibres, according to [IEC 60793-2-50] regarding the B-652.D fibre category.

NOTE 4 – According to clause 7.2, a maximum PMD_Q value on uncabled fibre is specified in order to support the primary requirement on cable PMD_Q.

NOTE 5 – Optical fibre cables with higher PMD coefficient can be used for systems with less stringent PMD requirements.

Appendix I

Information about cabled fibre link attributes used for system design

(This appendix does not form an integral part of this Recommendation.)

In order to estimate transmission limitation due to fibre properties including chromatic dispersion, PMD, attenuation and nonlinearity, "worst-case" and "statistical" system designs can be considered as is given in clauses 9 and 10 of [b-ITU-T G-Sup.39], respectively. The worst-case design is a deterministic methodology utilizing minimum and maximum values and is useful for a transmission system with a small number of components and spliced factory lengths of optical fibre cables. On the other hand, for a concatenated link that includes a large number of spliced factory lengths of optical fibre cable, the transmission parameters for the concatenated link must take into account not only the performance of the deterministic attributes of individual cable lengths but also the statistics of concatenation. The requirements for factory lengths are given in clauses 6 and 7.

The transmission characteristics of the factory length optical fibre cables will have a certain probability distribution which can be taken into account if the most economic designs are to be obtained. This appendix should be read with the statistical nature of the various parameters in mind.

Link attributes such as end-to-end attenuation, chromatic dispersion, PMD, or nonlinearity are affected by factors other than optical fibre cables, by such things as splices, passive components and installation. These factors are not specified in this Recommendation.

For the purpose of statistical link attribute values estimation for attenuation, chromatic dispersion typical values of optical fibre links are provided in Table I.1 in clause I.4. The estimation methods of link parameters needed for system design are based on measurements, modelling or other considerations.

I.1 Attenuation

The mean attenuation, A, of a link is given by:

$$A = \alpha L + \alpha_s x + \alpha_c y \tag{I-1}$$

where:

- α mean attenuation coefficient of the fibre cables in a link
- α_s mean splice loss
- x number of splices in a link
- α_c mean loss of line connectors
- y number of line connectors in a link (if provided)
- L link length.

A suitable margin should be allocated for future modifications of cable configurations (additional splices, extra cable lengths, ageing effects, temperature variations, etc.). The above equation does not include the loss of equipment connectors. The typical values found in clause I.4 are for the attenuation coefficient of optical fibre links. The attenuation budget used in designing an actual system should account for the statistical variations in these parameters.

I.2 Chromatic dispersion

The chromatic dispersion in ps/nm can be calculated from the chromatic dispersion coefficients of the factory lengths, assuming a linear dependence on length, and with due regard for the signs of the coefficients (see clause 6.10).

When these fibres are used for transmission in the 1550 nm region, some forms of chromatic dispersion compensation are often employed. In this case, the average link chromatic dispersion is used for design purposes. The measured dispersion in the 1550 nm window can be characterized within the 1550 nm window by a linear relationship with wavelength. The relationship is described in terms of the typical chromatic dispersion coefficient and dispersion slope coefficient at 1550 nm.

Typical values for the chromatic dispersion coefficient, D_{1550}, and chromatic dispersion slope coefficient, S_{1550}, at 1550 nm are found in Table I.1. These values, together with link length, L_{Link}, can be used to calculate the typical chromatic dispersion for use in optical link design.

$$D_{Link}(\lambda) = L_{Link}\left[D_{1550} + S_{1550}(\lambda - 1550)\right] \text{ [ps/nm]} \qquad \text{(I-2)}$$

NOTE – The normative chromatic dispersion specification has been revised for G.652.D fibres; therefore, this equation is no longer representative for this fibre type.

I.3 Differential group delay (DGD)

The differential group delay is the difference in arrival times of the two polarization modes at a particular wavelength and time. PMD is fundamentally statistical and DGD fluctuates with random behaviour at any longitudinal positions of fibre cables, and therefore, statistical link design methodology is essential to determine PMD impact when considering a link made of a certain length of or concatenated sections of fibre cables. For a link with a specific PMD coefficient, the DGD of the link varies randomly with time and wavelength as a Maxwell distribution that contains a single parameter, which is the product of the PMD coefficient of the link and the square root of the link length. The system impairment due to PMD at a specific time and wavelength depends on the DGD at that time and wavelength. So, means of establishing useful limits on the DGD distribution as it relates to the optical fibre cable PMD coefficient distribution and its limits have been developed and are documented in [b-IEC/TR 61282-3] and are summarized in Appendix IV of [ITU-T G.650.2]. The metrics of the limitations of the DGD distribution follow:

NOTE – The determination of the contribution of components other than optical fibre cable is beyond the scope of this Recommendation, but is discussed in [b-IEC/TR 61282-3].

Reference link length, L_{Ref}: A maximum link length to which the maximum DGD and probability will apply. For longer link lengths, multiply the maximum DGD by the square root of the ratio of actual length to the reference length.

Typical maximum cable length, L_{Cab}: The maxima are assured when the typical individual cables of the concatenation or the lengths of the cables that are measured in determining the PMD coefficient distribution are less than this value.

Maximum DGD, DGD_{max}: The DGD value that can be used when considering optical system design.

Maximum probability, P_F: The probability that an actual DGD value exceeds DGD_{max}.

I.4 Tables of common typical values

The values in Tables I.1 and I.2 are representative of concatenated optical fibre links according to clauses I.1 to I.3, respectively. The implied fibre induced maximum DGD values in Table I.2 are intended for guidance in regard to the requirements for other optical elements that may be in the link. Values presented in this clause apply to all G.652 compliant fibres including G.657.A fibres.

NOTE – Cable section length is 10 km except for the 0.10 ps/$\sqrt{\text{km}}$ /> 4 000 km link, where it is set to 25 km, the error probability level is 6.5×10^{-8}.

Table I.1 – Representative values of concatenated optical fibre links

Attenuation coefficient	Wavelength region	Typical link value
(Note)	1260 nm-1360 nm	0.5 dB/km
	1530 nm-1565 nm	0.275 dB/km
	1565 nm-1625 nm	0.35 dB/km
Chromatic dispersion parameter	D_{1550}	17 ps/(nm × km)
	S_{1550}	0.056 ps/(nm^2 × km)
NOTE – Typical link value corresponds to the link attenuation coefficient used in [b-ITU-T G.957] and [b-ITU-T G.691].		

Table I.2 – Differential group delay

Maximum PMD_Q [ps/ $\sqrt{km}$]	Link length [km]	Implied fibre induced maximum DGD [ps]	Channel bit rates
No specification			Up to 2.5 Gbit/s
0.5	400	25.0	10 Gbit/s
	40	19.0 (Note)	10 Gbit/s
	2	7.5	40 Gbit/s
0.20	3000	19.0	10 Gbit/s
	80	7.0	40 Gbit/s
0.10	>4000	12.0	10 Gbit/s
	400	5.0	40 Gbit/s
NOTE – This value applies also for 10 Gigabit Ethernet systems.			

I.5 Non-linear coefficient

The effect of chromatic dispersion is interactive with the non-linear coefficient, n_2/A_{eff}, regarding system impairments induced by non-linear optical effects (see [b-ITU-T G.663] and [ITU-T G.650.2]). Typical values vary with the implementation. The test methods for non-linear coefficient remain under study.

I.6 An example of statistical link design

I.6.1 An example of statistical link design methodology

A mathematical approach for statistical link design, can be taken when randomness can be assumed in designing a link (e.g., when a relatively large number of high-count cables are randomly concatenated to form a link), though its versatility is for further study. For example, when a concatenated link is composed of cabled fibre originated from a limited number of discrete fibres, randomness is limited, and the worst-case designing methodology is preferable to obtain reasonable system margins.

General methodology for statistical system design is described in [b-ITU-T G-Sup.39], and the following provides one way to formulate a statistical upper limit for one of fibre/cable parameters. The calculation starts with establishing a statistical distribution. Let x_i and L_i be a fibre parameter per unit length and a cable length, respectively, of a fibre in the i-th cable in a concatenated link of N cables. In the case a global fibre parameter in the total link x_N is in proportion the length, x_N is:

$$x_N = \frac{\sum_{i=1}^{N} L_i x_i}{\sum_{i=1}^{N} L_i} = \frac{1}{L_{Link}} \sum_{i=1}^{N} L_i x_i \quad \text{(I-3)}$$

If it is assumed that all cable section lengths are less than some common value, L_{Cab}, and simultaneously reducing the number of assumed cable sections to $M = L_{Link}/L_{Cab}$, then, for a link comprised of equal-length cables, $L_i = L_{Cab}$, equation above becomes

$$x_N \leq x_M = \frac{L_{Cab}}{L_{Link}} \sum_{i=1}^{M} x_i = \frac{1}{M} \sum_{i=1}^{M} x_i \quad \text{(I-4)}$$

The variation in the concatenated link parameter, x_M, will be less than the variation in the individual cable sections, xi, because of the averaging of the concatenated fibres.

Once distribution of the fibre parameter has been established, the Monte Carlo method can be used to determine the probability density, f_{link}, of the concatenated link fibre parameter without making any assumption about its form. This method simulates the process of building links by sampling the measured fibre parameter population repeatedly.

Fibre parameter is measured on a sufficiently large number of segments so as to characterise the underlying distribution. This data is then used to compute the fibre parameter for a single path in a concatenated link.

Computation is made by randomly selecting *M* values from the measured fibre parameters, and adding them according to equation (I-4). The computed concatenated attenuation is placed in a table or a histogram of values derived from other random samplings. The process is repeated until a sufficient number of concatenated attenuation values have been computed to produce a high-density histogram of concatenated distribution of the fibre parameter. If the histogram is used directly, without any additional characterization such as Gaussian fitting, the number of resamples should be at least 10^4.

Because of the central limit theorem, the histogram of the statistical values of fibre parameter in concatenated cabled link will tend to converge to distributions that can be described with a minimum of two parameters. Hence, the histogram can be fit to a parametric distribution that enables extrapolation to probability levels that are smaller than what would be implied by the sample size. The two parameters will invariably represent two aspects of the distributions: the central value and the variability about the central value.

To obtain probability levels of $Q = 10^{-3}$ using a pure numeric approach requires Monte Carlo simulations of at least 10^4 samples. Once this is complete, attenuation and/or chromatic dispersion distribution can be interpolated from the associated cumulative probability density functions.

It should be noted that the applicability of above example methodology is for further study.

I.6.2 Statistical design example for O-band chromatic dispersion in a link

A numerical case study for the statistical chromatic dispersion coefficient has been conducted based on the actual products of multiple fibre manufacturers, Corning, Fujikura, Furukawa Electric, OFS, Prysmian, Sterlite, Sumitomo Electric and YOFC. This case study assumed a link which is composed of 1, 4, 8, 12 or 16 concatenated cable pieces. The existing products compliant with G.652.D and G.657.A fibres were considered. The wavelength dependence of maximum/minimum chromatic dispersion values with probability (of exceeding link design value, LDV) Q of 10^{-4}, 10^{-3} and 10^{-2} were derived based on the actual zero-dispersion wavelength λ_0 and zero-dispersion wavelength slope S_0 properties of each manufacturer in the anonymous way. Then, the accumulated chromatic dispersion boundaries were established by using the maximum and minimum limit from the results of all the manufacturers.

Table I.3 summarizes the wavelength dependence of the maximum/minimum boundaries for chromatic dispersion coefficients in ps/(nm·km) when the number of concatenated cables M = 1, 4, 8 ,12 and 16. Thus, a corresponding chromatic dispersion can be derived by multiplying a $L \times M$ value to the chromatic dispersion coefficients, where L denotes a typical cable piece length in kilometres. Here, the chromatic dispersion coefficients at 1264.5 nm, 294.53 nm, 1310.19 nm, and 1337.5 nm were derived by assuming a linear wavelength dependence by using the examination values at a shorter and a longer wavelength.

Table I.3 – Statistical link wavelength dependence of the maximum/minimum chromatic dispersion coefficients when the number of concatenated cables *M* = 1, 4, 8, 12 or 16

Number of concatenated cables *M*		***M* = 1**			***M* = 4**			***M* = 8**			***M* = 12**			***M* = 16**		
Probability level *Q*		10^{-4}	10^{-3}	10^{-2}	10^{-4}	10^{-3}	10^{-2}	10^{-4}	10^{-3}	10^{-2}	10^{-4}	10^{-3}	10^{-2}	10^{-4}	10^{-3}	10^{-2}
Wavelength (nm)		**Statistical chromatic dispersion coefficient (ps/(nm·km))**														
Upper boundary	1260	−3.33	−3.94	−4.17	−4.21	−4.34	−4.45	−4.43	−4.48	−4.55	−4.46	−4.53	−4.58	−4.51	−4.56	−4.61
	1264.5	−2.95	−3.51	−3.73	−3.77	−3.90	−4.01	−3.99	−4.04	−4.11	−4.02	−4.09	−4.15	−4.08	−4.12	−4.17
	1270	−2.50	−2.99	−3.20	−3.23	−3.36	−3.48	−3.46	−3.51	−3.58	−3.49	−3.56	−3.62	−3.55	−3.59	−3.64
	1280	−1.68	−2.07	−2.25	−2.28	−2.42	−2.54	−2.52	−2.57	−2.64	−2.54	−2.62	−2.68	−2.61	−2.65	−2.70
	1290	−0.88	−1.15	−1.33	−1.35	−1.50	−1.63	−1.59	−1.65	−1.73	−1.63	−1.71	−1.77	−1.70	−1.74	−1.79
	1294.53	−0.49	−0.74	−0.92	−0.94	−1.10	−1.22	−1.18	−1.25	−1.33	−1.23	−1.30	−1.36	−1.30	−1.33	−1.39
	1300	−0.03	−0.24	−0.43	−0.44	−0.61	−0.74	−0.69	−0.76	−0.84	−0.74	−0.82	−0.88	−0.81	−0.85	−0.89
	1310	0.87	0.65	0.44	0.45	0.26	0.13	0.20	0.11	0.03	0.13	0.05	0.01	0.06	0.02	−0.01
	1310.19	0.89	0.67	0.46	0.47	0.28	0.15	0.22	0.12	0.05	0.14	0.06	0.02	0.07	0.04	0.01
	1320	1.75	1.53	1.30	1.32	1.11	0.98	1.07	0.95	0.90	0.97	0.91	0.88	0.91	0.89	0.86
	1324	2.10	1.87	1.63	1.66	1.44	1.31	1.42	1.29	1.24	1.31	1.25	1.22	1.25	1.23	1.20
	1330	2.62	2.38	2.13	2.17	1.94	1.81	1.92	1.79	1.75	1.81	1.76	1.72	1.76	1.74	1.71
	1337.5	3.24	3.01	2.77	2.79	2.55	2.44	2.54	2.42	2.37	2.43	2.38	2.35	2.39	2.36	2.33
	1340	3.45	3.22	2.98	3.00	2.75	2.65	2.75	2.64	2.58	2.64	2.59	2.55	2.60	2.57	2.54
	1350	4.28	4.04	3.82	3.81	3.59	3.48	3.56	3.47	3.41	3.47	3.42	3.37	3.43	3.40	3.35
Lower boundary	1260	−6.34	−6.27	−6.10	−5.98	−5.90	−5.81	−5.86	−5.80	−5.74	−5.79	−5.75	−5.70	−5.76	−5.72	−5.68
	1264.5	−5.87	−5.80	−5.63	−5.51	−5.44	−5.35	−5.39	−5.34	−5.28	−5.33	−5.29	−5.24	−5.30	−5.26	−5.22
	1270	−5.29	−5.22	−5.07	−4.95	−4.87	−4.79	−4.83	−4.77	−4.71	−4.76	−4.73	−4.68	−4.73	−4.70	−4.66
	1280	−4.25	−4.20	−4.07	−3.94	−3.87	−3.79	−3.83	−3.77	−3.71	−3.76	−3.73	−3.68	−3.73	−3.70	−3.66
	1290	−3.25	−3.20	−3.08	−3.02	−2.89	−2.81	−2.85	−2.80	−2.74	−2.79	−2.76	−2.71	−2.76	−2.73	−2.69
	1294.53	−2.81	−2.76	−2.65	−2.61	−2.46	−2.38	−2.41	−2.37	−2.31	−2.36	−2.32	−2.28	−2.33	−2.30	−2.26
	1300	−2.27	−2.23	−2.13	−2.11	−1.94	−1.86	−1.89	−1.84	−1.79	−1.84	−1.80	−1.76	−1.81	−1.78	−1.74
	1310	−1.31	−1.28	−1.19	−1.23	−1.01	−0.93	−0.98	−0.92	−0.86	−0.91	−0.88	−0.83	−0.88	−0.85	−0.81
	1310.19	−1.29	−1.26	−1.17	−1.21	−0.99	−0.91	−0.96	−0.90	−0.84	−0.89	−0.86	−0.81	−0.86	−0.83	−0.80
	1320	−0.37	−0.36	−0.28	−0.36	−0.10	−0.02	−0.12	−0.01	0.05	−0.01	0.03	0.07	0.03	0.06	0.09
	1324	0.00	0.00	0.08	0.00	0.26	0.33	0.21	0.35	0.40	0.35	0.39	0.43	0.38	0.41	0.45
	1330	0.44	0.54	0.61	0.48	0.79	0.86	0.73	0.88	0.93	0.84	0.92	0.96	0.90	0.94	0.98
	1337.5	0.97	1.17	1.26	1.10	1.44	1.51	1.35	1.53	1.58	1.46	1.56	1.61	1.52	1.59	1.63
	1340	1.15	1.39	1.48	1.31	1.65	1.73	1.55	1.74	1.80	1.67	1.78	1.83	1.73	1.81	1.84
	1350	1.85	2.23	2.33	2.11	2.50	2.57	2.36	2.58	2.62	2.47	2.61	2.65	2.54	2.63	2.66

A fitting equation for the wavelength dependence of the maximum/minimum chromatic dispersion coefficients for M = 1, 4, 8, 12, or 16 at corresponding Q level is derived as an example by assuming Eq. (I-5).

$$D = \frac{\lambda S_0}{4}\left\{1 - \left(\frac{\lambda_0}{\lambda}\right)^4\right\} \tag{I-5}$$

where D, λ_0, and S_0 denote chromatic dispersion coefficient in ps/(nm × km), zero-dispersion wavelength in nm, and zero-dispersion wavelength slope in ps/(nm^2 × km), respectively. Table I.4 summarizes the example fitting results for M = 4, 8, 12, and 16. Here, two fitting wavelength regions, shorter or longer than λ_0, are considered because the examination results contain various combination of the λ_0 and S_0 values. It should be noted that the applicability of the derived fitting coefficients may be degraded particularly when M is less than four since it is difficult to expect sufficient statistical benefit. The maximum/minimum chromatic dispersion coefficients become almost comparable with the worst-case boundaries particularly when M = 1.

Table I.4 – Example fitting coefficients for Eq. (I-5) and maximum approximation errors for the statistical chromatic dispersion coefficients in the O-band for *M* = 4, 8, 12 and 16

		Example fitting coefficients											
Number of concatenated cables *M*		***M* = 4**			***M* = 8**			***M* = 12**			***M* = 16**		
Probability level *Q*		10^{-4}	10^{-3}	10^{-2}	10^{-4}	10^{-3}	10^{-2}	10^{-4}	10^{-3}	10^{-2}	10^{-4}	10^{-3}	10^{-2}
Upper boundary	λ_0	1304.9	1307.0	1308.5	1307.7	1308.8	1309.7	1308.6	1309.4	1309.9	1309.4	1309.7	1310.1
	S_0 ($\lambda < \lambda_0$)	0.089	0.087	0.086	0.088	0.086	0.086	0.086	0.086	0.087	0.086	0.086	0.087
	S_0 ($\lambda > \lambda_0$)	0.089	0.087	0.087	0.088	0.087	0.088	0.087	0.088	0.088	0.088	0.088	0.088
Lower boundary	λ_0	1324.0	1321.1	1320.3	1321.4	1320.1	1319.5	1320.1	1319.7	1319.2	1319.7	1319.4	1319.0
	S_0 ($\lambda < \lambda_0$)	0.086	0.090	0.090	0.088	0.090	0.090	0.090	0.090	0.090	0.090	0.090	0.090
	S_0 ($\lambda > \lambda_0$)	0.083	0.089	0.089	0.085	0.089	0.089	0.086	0.089	0.089	0.087	0.089	0.089
Maximum approximation error (ps/(nm × km))		0.039	0.035	0.037	0.055	0.038	0.015	0.031	0.022	0.014	0.025	0.013	0.016
NOTE – λ_0 in nm and S_0 in ps/(nm^2 × km)													

Another way to estimate the LDV limits on chromatic dispersion coefficient D for cable concatenations with different values of M and/or different probability level Q can be obtained using the examination data shown in Table I.3. It is assumed that the probability density function $f_D(x)$ of the link distribution dispersion coefficient for the several fibre manufacturers looks something like that shown in Figure I.1. The key feature here is that there are manufacturers at the high and low ends of $f_D(x)$ which can be represented by partial distributions, roughly Gaussian in shape, which govern the LDV. These distributions may change depending on M and wavelength.

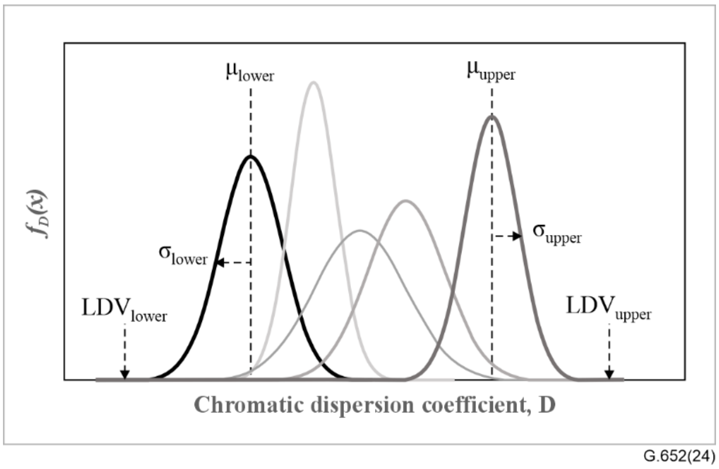

Figure I.1 – Assumed composite distribution with two partial limiting distributions which set the LDV limits

Employing the central limit theorem (which allows the assumption of Gaussian distribution shapes as $M >> 1$), the LDV limits may be found by scaling from the Gaussian parameters found in Table I.5, for the partial distributions for the reference $M = M_0 = 4$ case.

Table I.5 – Gaussian parameters for the upper and lower partial distributions of $f_D(x)$ for the reference case, $M = M_0 = 4$

Wavelength (nm)	Gaussian parameters (ps/(nm × km))			
	μ_{lower}	σ_{lower}	μ_{upper}	σ_{upper}
1260	−5.536	0.119	−4.818	0.161
1270	−4.518	0.116	−3.859	0.165
1280	−3.522	0.114	−2.939	0.173
1290	−2.489	0.141	−2.048	0.186
1300	−1.483	0.166	−1.179	0.197
1310	−0.502	0.192	−0.334	0.210
1320	0.441	0.214	0.504	0.218
1324	0.784	0.211	0.838	0.221
1330	1.327	0.227	1.342	0.220
1340	2.153	0.227	2.184	0.217
1350	2.969	0.231	3.034	0.206

To compute approximate chromatic dispersion coefficient link design value limits, from the parameters of Table I.5 given a new M and Q, use equations (I-6) and (I-7).

$$LDV_{upper} = \mu_{upper} + \sigma_{upper}(M_0)\sqrt{2}\, erf^{-1}(1-2Q)\sqrt{\frac{M_0}{M}} \qquad \text{(I-6)}$$

$$LDV_{lower} = \mu_{lower} - \sigma_{lower}(M_0)\sqrt{2}\, erf^{-1}(1-2Q)\sqrt{\frac{M_0}{M}} \qquad \text{(I-7)}$$

where the μ and σ parameters of these equations are listed in Table I.5 for the wavelength of interest. This approximation is not expected to work well for small M (i.e., $M = 1$).

I.6.3 Influence of number of concatenated cable pieces M on PMD_Q and DGD

As described in clause 7.2, PMD_Q variation depends on the number of concatenated cable pieces M. The specification tables found in clause 8 assume $M = 20$ and $Q = 10^{-4}$ as an example. Table I.6 provides example dependence of mean PMD_Q and mean DGD on the M value. Here, mean normalized PMD_Q or DGD denotes numerically expected PMD_Q or DGD values when M varies from 20, and these values are normalized with the PMD_Q or DGD values at $M = 20$. It is assumed that probability distribution of PMD or DGD follows a Maxwellian distribution. Table I.6 shows that mean normalized PMD_Q tends to degrade as decreasing the M value, although mean normalized DGD value decreases. It should be noted that Table I.6 provides a numerical example, and it does not ensure the actual dependence on M value.

Table I.6 – Example dependence of mean normalized PMDQ and mean normalized DGD on the number of concatenated cable pieces M

Number of concatenated cables *M*	Mean normalized PMD_Q	Mean normalized DGD
4	1.32	0.59
10	1.13	0.80
20	1.00	1.00
30	0.96	1.17

Appendix II

Information on data collection of G.652.D fibre maximum/minimum chromatic dispersion for boundary line specification

(This appendix does not form an integral part of this Recommendation.)

In November 2014 ITU-T SG15/Q5 decided to enhance the specification of the chromatic dispersion of existing G.652.D fibres and to express this new specification in terms of maximum and minimum boundary lines in the 1270-1625 nm wavelength region. For that purpose, an investigation of the chromatic dispersion has been undertaken in cooperation with eight major fibre vendors, all members of ITU-T SG15/Q5 as of the time of the study. In this examination all G.652.D type fibres were included, including G.657.A fibres and pure silica core-based G.652.D fibres. The examination took place in an anonymous manner.

The results of this investigation are visible in Figure II.1.

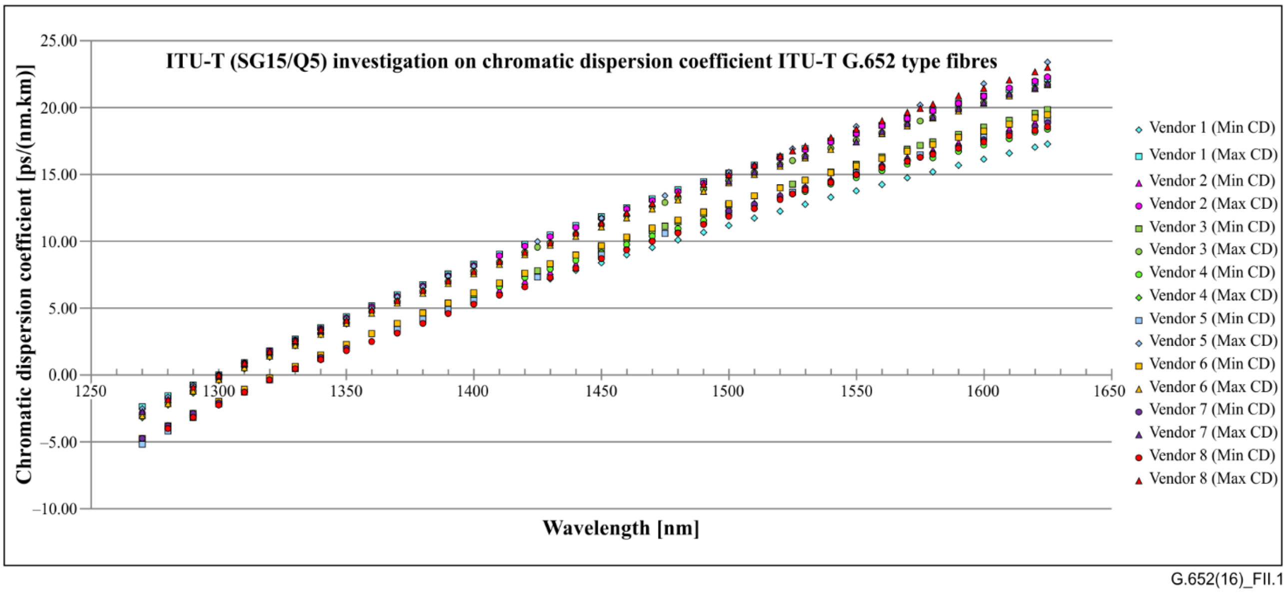

Figure II.1 – Investigation on maximum and minimum chromatic dispersion coefficient for G.652.D type fibres over the wavelength range 1270 nm to 1625 nm

Table II.1 shows the collected data of chromatic dispersion over the wavelength range 1270 nm to 1625 nm, as received from 8 fibre vendors.

Based on this data set, a maximum and minimum boundary line specification for the chromatic dispersion of G.652.D type fibres has been developed. See Table 2 in clause 8, first introduced in edition 9 (2016) of this Recommendation.

Table II.1 – Investigation on maximum and minimum chromatic dispersion coefficient for G.652.D type fibres over the wavelength range 1270 nm to 1625 nm

ITU-T SG15/Q5 Chrom. Dispersion data gathering G.652 type fibre manufacturers — Date: 2015-04-21

Chromatic Dispersion Coefficient [ps/(nm.km)]

Wavelength (nm)	Vendor 1 (Min CD)	Vendor 1 (Max CD)	Vendor 2 (Min CD)	Vendor 2 (Max CD)	Vendor 3 (Min CD)	Vendor 3 (Max CD)	Vendor 4 (Min CD)	Vendor 4 (Max CD)	Vendor 5 (Min CD)	Vendor 5 (Max CD)	Vendor 6 (Min CD)	Vendor 6 (Max Cd)	Vendor 7 (Min CD)	Vendor 7 (Max CD)	Vendor 8 (Min CD)	Vendor 8 (Max CD)
1270	-4,96	-2,36	-4,82	-2,83	-4,74	-3,14	-4,83	-3,18	-5,18	-2,54	-4,80	-3,05	-4,70	-2,76		
1280	-3,99	-1,56	-3,87	-1,88	-3,79	-2,18	-3,87	-2,26	-4,18	-1,68	-3,83	-2,12	-3,80	-1,82	-3,99	-1,83
1290	-3,05	-0,77	-2,96	-0,94	-2,86	-1,25	-2,94	-1,34	-3,19	-0,83	-2,89	-1,21	-2,90	-0,91	-3,16	-0,92
1300	-2,12	0,00	-2,06	-0,02	-1,96	-0,33	-2,03	-0,43	-2,17	-0,01	-1,97	-0,32	-2,10	-0,10	-2,25	0,00
1310	-1,23	0,91	-1,18	0,88	-1,08	0,56	-1,14	0,46	-1,28	0,89	-1,07	0,55	-1,20	0,84	-1,28	0,92
1320	-0,35	1,81	-0,33	1,76	-0,22	1,44	-0,28	1,33	-0,35	1,75	-0,20	1,41	-0,40	1,68	-0,32	1,77
1330	0,45	2,68	0,50	2,62	0,61	2,29	0,56	2,19	0,49	2,61	0,65	2,24	0,50	2,50	0,48	2,60
1340	1,19	3,53	1,31	3,47	1,43	3,13	1,38	3,03	1,25	3,41	1,49	3,06	1,30	3,30	1,17	3,42
1350	1,92	4,37	2,10	4,29	2,23	3,94	2,19	3,85	2,01	4,25	2,30	3,86	2,00	4,08	1,84	4,15
1360	2,63	5,19	2,87	5,10	3,01	4,75	2,97	4,65	2,75	5,04	3,10	4,64	2,80	4,90	2,49	4,88
1370	3,32	5,99	3,55	5,90	3,79	5,51	3,73	5,44	3,47	5,83	3,88	5,39			3,13	5,59
1380	4,00	6,78	4,28	6,68	4,55	6,27	4,47	6,21	4,17	6,58	4,65	6,13			3,87	6,33
1390	4,67	7,54	4,98	7,44	5,29	7,02	5,19	6,97	4,88	7,39	5,41	6,86			4,59	7,05
1400	5,32	8,30	5,68	8,19	6,02	7,76	5,91	7,72	5,58	8,14	6,15	7,58			5,29	7,77
1410	5,96	9,04	6,37	8,92	6,74	8,48	6,60	8,45			6,88	8,30			5,96	8,49
1420	6,58	9,76	7,05	9,65	7,44	9,19	7,27	9,18			7,60	9,01			6,61	9,20
1425					7,79	9,55			7,31	9,97						
1430	7,20	10,47	7,72	10,35	8,14	9,89	7,94	9,89			8,31	9,71			7,29	9,91
1440	7,80	11,17	8,31	11,05	8,82	10,58	8,58	10,58			9,00	10,40			7,99	10,64
1450	8,39	11,86	8,99	11,73	9,50	11,26	9,18	11,27	8,98	11,71	9,67	11,08			8,71	11,35
1460	8,97	12,53	9,66	12,41	10,16	11,93	9,79	11,94			10,33	11,76			9,35	12,11
1470	9,54	13,19	10,32	13,07	10,82	12,59	10,40	12,61			10,98	12,42			9,98	12,82
1475					11,15	12,92			10,60	13,40						
1480	10,10	13,84	10,96	13,72	11,45	13,22	10,99	13,26			11,61	13,08			10,63	13,54
1490	10,65	14,48	11,59	14,36	12,10	13,87	11,57	13,90			12,23	13,73			11,26	14,27
1500	11,19	15,10	12,21	14,99	12,74	14,51	12,13	14,53	12,16	15,16	12,83	14,37	12,30	14,50	11,87	14,99
1510	11,72	15,72	12,82	15,61	13,36	15,14	12,68	15,15			13,42	15,00	12,80	15,20	12,45	15,68
1520	12,24	16,33	13,42	16,23	13,98	15,76	13,21	15,76			14,00	15,63	13,40	15,80	13,11	16,40
1525					14,28	16,06			13,66	16,89					13,55	16,79
1530	12,76	16,93	14,01	16,83	14,59	16,37	13,74	16,36			14,56	16,25	14,00	16,40	13,84	17,12
1540	13,26	17,51	14,59	17,43	15,18	16,97	14,27	16,94			15,12	16,85	14,50	17,00	14,40	17,76
1550	13,76	18,09	15,16	18,02	15,76	17,56	14,78	17,52	15,10	18,56	15,66	17,45	15,00	17,50	14,94	18,39
1560	14,25	18,66	15,73	18,60	16,33	18,14	15,28	18,10			16,20	18,05	15,60	18,20	15,50	19,01
1570	14,73	19,22	16,28	19,18	16,89	18,71	15,78	18,66			16,73	18,63	16,10	18,80	15,99	19,63
1575					17,17	18,99			16,48	20,20					16,29	19,93
1580	15,20	19,78	16,82	19,76	17,45	19,27	16,27	19,21			17,24	19,21	16,60	19,30	16,49	20,25
1590	15,67	20,32	17,36	20,33	17,99	19,83	16,75	19,76			17,75	19,77	17,10	19,90	16,95	20,88
1600	16,13	20,86	17,89	20,89	18,53	20,37	17,23	20,30	17,81	21,81	18,25	20,33	17,60	20,40	17,46	21,45
1610	16,59	21,39	18,41	21,45	19,06	20,91	17,70	20,83			18,75	20,89	18,10	21,00	17,89	22,08
1620	17,03	21,91	18,92	22,01	19,58	21,44	18,17	21,36			19,23	21,43	18,60	21,50	18,31	22,69
1625	17,25	22,17	19,17	22,28	19,84	21,71	18,40	21,62	19,09	23,38	19,47	21,70	18,90	21,80	18,60	23,01

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