

Recommendation  
**ITU-T G.654 (08/2024)**

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

Transmission media and optical systems characteristics – Optical fibre cables

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**Characteristics of a cut-off shifted single-mode optical fibre and cable**



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# Recommendation ITU-T G.654

## Characteristics of a cut-off shifted single-mode optical fibre and cable

### Summary

Recommendation ITU-T G.654 describes the geometrical, mechanical and transmission attributes of a single-mode optical fibre and cable which has the zero-dispersion wavelength around 1300 nm wavelength, and which is loss-minimized and cut-off wavelength shifted at around the 1550 nm wavelength region. This is the latest revision of this Recommendation that was first created in 1988.

### History \*

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Cut-off shifted single-mode optical fibre and cable, large mode field diameter fibre, long haul transmission, optical fibre and cable.

\* 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

History of this Recommendation since it was first approved in 1988.

- 1988 Recommendation ITU-T G.654, *Characteristics of a 1550 nm wavelength loss-minimized single-mode optical fibre cable*, was created.
- 2000 The fourth version of Recommendation ITU-T G.654 changed the Recommendation structure, in accordance with other fibre Recommendations such as ITU-T G.652, G.653 and G.655.
- 2002 The fifth version of Recommendation ITU-T G.654 added a new fibre category with changed fibre attributes of mode field diameter and chromatic dispersion coefficient as G.654.B. According to the agreement on spectral bands, description of L-band upper limit was changed from 16xx nm to 1625 nm. The terms of base subcategory and subcategory were revised to base category and category, respectively.
- 2004 The sixth version of Recommendation ITU-T G.654 reduced PMD<sub>Q</sub> limit from 0.5 ps/√km to 0.2 ps/√km in G.654.B and added a new category G.654.C which has the reduced PMD<sub>Q</sub> limit. Tolerance of mode field diameter in G.654.B was also reduced to ±0.7 μm. For the macrobending test, mandrel radius is reduced to 30 mm.
- 2006 The seventh version of Recommendation ITU-T G.654 changed the notation of PMD in order to make it consistent with that of Recommendation ITU-T G.652.
- 2010 The eighth version of Recommendation ITU-T G.654 removed the jumper cut-off wavelength definition and added notes allowing higher maximum cabled attenuation for short cables such as jumper cables.
- 2012 The ninth version of Recommendation ITU-T G.654 introduced category G.654.D in order to improve the optical signal to noise ratio (OSNR) characteristics, e.g., which can be applied to higher bit-rate submarine systems.
- 2016 The tenth version of Recommendation ITU-T G.654 introduced category G.654.E in order to significantly improve the optical signal to noise ratio (OSNR) characteristics to support 100 Gbit/s and beyond 100 Gbit/s digital coherent transmission systems in terrestrial deployments.
- 2020 The eleventh version of Recommendation ITU-T G.654 changed the attenuation coefficient of ITU-T G.654.E to specify a wavelength dependency for estimating optical system design. A note was also added for cable cut-off wavelength when ITU-T G.654.E fibre is used at central frequencies for applications specified in Recommendation ITU-T G.698.2.
- 2024 The twelfth version of Recommendation ITU-T G.654 removed fibre cut-off wavelength recommendation and a note regarding cut-off wavelength in WDM applications. Meanwhile, a new note for cut-off wavelength property under a unique deployment condition are added. In a note for cable cut-off wavelength when G.654.E fibre is used at central frequencies for applications specified in Recommendation ITU-T G.698.2, the upper limit was changed from 1527.8 nm to 1527 nm considering the measurement accuracy. This revision is intended to maintain the continuing commercial success of this fibre in the evolving world of high-performance optical transmission systems.

# Recommendation ITU-T G.654

## Characteristics of a cut-off shifted single-mode optical fibre and cable

### 1 Scope

This Recommendation describes a single-mode optical fibre and cable, which has the zero-dispersion wavelength around 1300 nm, which is loss-minimized and cut-off shifted at a wavelength around 1550 nm and which is optimized for use in the 1530-1625 nm region.

This very low loss cut-off shifted fibre (CSF) can be used for long-distance digital transmission applications, such as long-haul terrestrial line systems and submarine cable systems using optical amplifiers. The geometrical, optical transmission (attenuation, cut-off wavelength, chromatic dispersion and polarization mode dispersion (PMD), etc.), and mechanical characteristics of this CSF are described.

Some provisions are made to support transmission at higher wavelengths up to 1625 nm. The geometrical, optical transmission, and mechanical parameters are described in three categories of attributes:

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

This Recommendation, and the different performance categories found in Tables 1 to 5 in clause 8, are intended to support the following related-system Recommendations:

Category	Recommendations
Characteristics of optical systems	[b-ITU-T G.696.1]
Digital line systems	[b-ITU-T G.957]
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]

The meaning of the terms used in this Recommendation, and the guidelines to be followed in the measurements 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*.

[ITU-T G.652]	Recommendation ITU-T G.652 (2024), <i>Characteristics of a single-mode optical fibre and cable</i> .
[ISO 80000-1]	ISO 80000-1:2022, <i>Quantities and units – Part 1: General</i> .

### 3 Definitions

#### 3.1 Terms defined elsewhere

This Recommendation uses the terms given in [ITU-T G.650.1] and [ITU-T G.650.2].

#### 3.2 Terms defined in this Recommendation

None.

### 4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

CSF	Cut-off Shifted Fibre
DGD	Differential Group Delay
DWDM	Dense Wavelength Division Multiplexing
MFD	Mode Field Diameter
OSNR	Optical Signal to Noise Ratio
PMD	Polarization Mode Dispersion
PMD <sub>Q</sub>	Statistical parameter for link PMD
TBD	To Be Determined
WDM	Wavelength Division Multiplexing

### 5 Conventions

Values shall be rounded to the number of digits in the recommended values listed in Tables 1 to 5 before conformance is evaluated. The conventional rule of "rounding half away from zero" is used, which is described in rule B of Annex 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 that provide a minimum essential design framework for fibre manufacturers are recommended in this clause. Ranges or limits on values are presented in Tables 1 to 5 in clause 8. Of these, cable manufacture or installation may significantly affect the cabled fibre cut-off wavelength and polarization mode dispersion (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 of mode field diameter (MFD) shall be specified at 1550 nm. The nominal values of the MFD that are specified shall be within the ranges found in clause 8. The specified tolerance of the MFD 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,  $\lambda_{cc}$ ;
- b) fibre cut-off wavelength,  $\lambda_c$ .

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

The correlation of the measured values of  $\lambda_c$  and  $\lambda_{cc}$  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  $\lambda_{cc}$  of a cabled single-mode fibre to be 1530 nm.

NOTE 2 – Cut-off wavelength intrinsically contains length or bending dependence. In the case of a unique deployment condition is 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 value of  $\lambda_{cc}$  shall not exceed 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 are chosen for implementation, it is suggested that not less than 40 turns and 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 – If 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 from 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 a single-jacketed fibre, similar indications shall be given.

### 6.7.3 Proof stress level

The specified proof stress,  $\sigma_p$ , 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 6.7 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

For DWDM operations in the 1550 nm region, the chromatic dispersion of ITU-T G.654 fibres is large enough to avoid four-wave mixing. Chromatic dispersion uniformity is therefore not a functional issue.

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 dense wavelength division multiplexing (DWDM) 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.

## 6.10 Chromatic dispersion

The measured group delay or chromatic dispersion per unit fibre length versus wavelength can be fitted by the quadratic equation defined 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.) As found in clause 8, at 1550 nm, the chromatic dispersion value shall not exceed the maximum value, the  $D_{1550\text{max}}$ , or shall be between the minimum value,  $D_{1550\text{min}}$ , and  $D_{1550\text{max}}$ . Also, at 1550 nm, the dispersion slope value shall not exceed the maximum value, the  $S_{1550\text{max}}$ , or shall be between the minimum value,  $S_{1550\text{min}}$ , and  $S_{1550\text{max}}$ .

Depending on accuracy requirements, for wavelength bandwidth of up to 35 nm, the quadratic equation is allowed in the 1550 nm region. For C- and L-band operation, either the five-term Sellmeier model or the 4<sup>th</sup> order polynomial model is recommended. The quadratic equation is not meant to be used in the 1 310 nm region.

NOTE – It is not necessary to measure the chromatic dispersion coefficient on a routine basis.

For sub-category G.654.E fibre, the chromatic dispersion parameters indicated in Table 5 in clause 8 are specified in order to bind the minimum/maximum chromatic dispersion coefficient  $D(\lambda)$  at wavelength  $\lambda$  from 1530 nm to 1625 nm. This allows more accurate system design, in which dispersion-compensating schemes are incorporated. The quadratic fitting for the group delay found in Table A.1 of [ITU-T G.650.1] is applied, and the  $D(\lambda)$  is bound by the following inequality:

$$D_{1550\text{min}} + S_{1550\text{min}}(\lambda - 1550) \leq D(\lambda) \leq D_{1550\text{max}} + S_{1550\text{max}}(\lambda - 1550), \quad (6-1)$$

where  $D_{1550\text{min}}$ ,  $D_{1550\text{max}}$ ,  $S_{1550\text{min}}$ , and  $S_{1550\text{max}}$  are listed in Table 5 in clause 8.

## 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 the 1530-1625 nm region. The optical fibre cable attenuation coefficient values shall not exceed the values found in clause 8.

NOTE 1 – The lowest values depend on the fabrication process, fibre composition and design, and cable design. Values of 0.15 dB/km to 0.19 dB/km in the 1550 nm region have been achieved.

NOTE 2 – The attenuation coefficient may be calculated across an entire spectrum, based on measurements at a few predictor wavelengths. This procedure is described in clause 6.4.4 of [ITU-T G.650.1] and an example for ITU-T G.654 fibre is given in Appendix III of [ITU-T G.650.1].

NOTE 3 – For applications of submarine systems with remotely pumped optical amplifiers described in [b-ITU-T G.973], other attenuation coefficients in the pump wavelength region may be required.

### 7.2 Polarization mode dispersion coefficient

Cabled fibre PMD 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 in this clause. Methods of calculation 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,  $\text{PMD}_Q$ , that 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  $\text{PMD}_Q$ . For the values of  $M$  and  $Q$  given in clause 8, the value of  $\text{PMD}_Q$  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 –  $\text{PMD}_Q$  should be calculated for various types of cables, and they should usually be calculated using sampled PMD values. The samples are taken from cables of similar construction.

NOTE 2 – The  $\text{PMD}_Q$  specification should not be applied to short cables such as jumper cables, indoor cables and drop cables.

## 8 Recommended value tables

Tables 1 to 5 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 requirements for MFD, chromatic dispersion coefficient and PMD. See Appendix I for information about transmission distances and bit rates relative to PMD requirements.

Table 1, ITU-T G.654.A attributes, is the base category for a cut-off shifted single-mode optical fibre and cable. This category is suitable for the system in [b-ITU-T G.696.1], [b-ITU-T G.957], [b-ITU-T G.973], [b-ITU-T G.973.1], [b-ITU-T G.973.2], and [b-ITU-T G.977.1] in the 1550 nm wavelength region.

Table 2, ITU-T G.654.B attributes, is suitable for the system described in [b-ITU-T G.696.1], [b-ITU-T G.957] long-haul application in the 1550 nm wavelength region. This category can be applied to longer distance and larger capacity WDM transmission systems, e.g., repeaterless submarine systems described in [b-ITU-T G.973], [b-ITU-T G.973.1] and [b-ITU-T G.973.2], and submarine systems with optical amplifiers described in [b-ITU-T G.977.1].

Table 3, ITU-T G.654.C attributes, is similar to ITU-T G.654.A, but the reduced PMD requirement supports higher bit-rate and long-haul applications in [b-ITU-T G.696.1], [b-ITU-T G.957], [b-ITU-T G.973], [b-ITU-T G.973.1], [b-ITU-T G.973.2], and [b-ITU-T G.977.1].

Table 4, ITU-T G.654.D attributes, is similar to ITU-T G.654.B, but has a modified macrobending loss specification as well as lower attenuation and larger MFD to improve the optical signal to noise ratio (OSNR) characteristics. This category is recommended for higher bit-rate submarine systems described in [b-ITU-T G.957], [b-ITU-T G.973], [b-ITU-T G.973.1], [b-ITU-T G.973.2], and [b-ITU-T G.977.1].

Table 5, ITU-T G.654.E attributes, is similar to ITU-T G.654.B, but has a smaller macrobending loss specification equivalent to ITU-T G.652.D fibres, tightened range of nominal MFD and the minimum/maximum chromatic dispersion in the wavelength range of 1530 nm to 1625 nm for deployment as terrestrial cables with improved OSNR characteristics to support higher bit-rate coherent transmission, e.g., 100 Gbit/s systems.

**Table 1 – ITU-T G.654.A attributes**

<b>Fibre attributes</b>			
<b>Attribute</b>	<b>Detail</b>	<b>Value</b>	<b>Unit</b>
Mode field diameter	Wavelength	1550	nm
	Range of nominal values	9.5-10.5	µm
	Tolerance	±0.7	µm
Cladding diameter	Nominal	125	µm
	Tolerance	±1	µm
Core concentricity error	Maximum	0.8	µm
Cladding non-circularity	Maximum	2.0	%
Cable cut-off wavelength	Maximum	1530	nm
Macrobending loss	Radius	30	mm
	Number of turns	100	
	Maximum at 1625 nm	0.50	dB
Proof stress	Minimum	0.69	GPa
Chromatic dispersion parameter	$D_{1550\text{max}}$	20	ps/(nm × km)
	$S_{1550 \text{ max}}$	0.070	ps/(nm <sup>2</sup> × km)
Uncabled fibre PMD coefficient	Maximum	(Note 2)	
<b>Cable attributes</b>			
<b>Attribute</b>	<b>Detail</b>	<b>Value</b>	<b>Unit</b>
Attenuation coefficient (Note 1)	Maximum at 1550 nm	0.22	dB/km
PMD coefficient (Note 2)	$M$	20	cables
	$Q$	0.01	%
	Maximum $\text{PMD}_Q$	0.5	ps/√km
NOTE 1 – The attenuation coefficient values listed in this table should not be applied to short cables such as jumper cables. For example, [b-IEC 60794-2-11] specifies the attenuation coefficient of indoor cable as 1.0 dB/km or less.			
NOTE 2 – According to clause 7.2, a maximum $\text{PMD}_Q$ value on uncabled fibre is specified in order to support the primary requirement on cable $\text{PMD}_Q$ .			

**Table 2 – ITU-T G.654.B attributes**

<b>Fibre attributes</b>			
<b>Attribute</b>	<b>Detail</b>	<b>Value</b>	<b>Unit</b>
Mode field diameter	Wavelength	1550	nm
	Range of nominal values	9.5-13.0	µm
	Tolerance	±0.7	µm
Cladding diameter	Nominal	125	µm
	Tolerance	±1	µm
Core concentricity error	Maximum	0.8	µm
Cladding non-circularity	Maximum	2.0	%
Cable cut-off wavelength	Maximum	1530	nm
Macrobending loss	Radius	30	mm
	Number of turns	100	
	Maximum at 1625 nm	0.50	dB
Proof stress	Minimum	0.69	GPa
Chromatic dispersion parameter	$D_{1550\text{max}}$	22	ps/(nm × km)
	$S_{1550\text{max}}$	0.070	ps/(nm <sup>2</sup> × km)
Uncabled fibre PMD coefficient	Maximum	(Note 2)	
<b>Cable attributes</b>			
<b>Attribute</b>	<b>Detail</b>	<b>Value</b>	<b>Unit</b>
Attenuation coefficient (Note 1)	Maximum at 1550 nm	0.22	dB/km
PMD coefficient (Note 2)	$M$	20	cables
	$Q$	0.01	%
	Maximum $\text{PMD}_Q$	0.20	ps/√km
NOTE 1 – The attenuation coefficient values listed in this table should not be applied to short cables such as jumper cables. For example, [b-IEC 60794-2-11] specifies the attenuation coefficient of indoor cable as 1.0 dB/km or less.			
NOTE 2 – According to clause 7.2, a maximum $\text{PMD}_Q$ value on uncabled fibre is specified in order to support the primary requirement on cable $\text{PMD}_Q$ .			

**Table 3 – ITU-T G.654.C attributes**

<b>Fibre attributes</b>			
<b>Attribute</b>	<b>Detail</b>	<b>Value</b>	<b>Unit</b>
Mode field diameter	Wavelength	1550	nm
	Range of nominal values	9.5-10.5	µm
	Tolerance	±0.7	µm
Cladding diameter	Nominal	125	µm
	Tolerance	±1	µm
Core concentricity error	Maximum	0.8	µm
Cladding non-circularity	Maximum	2.0	%
Cable cut-off wavelength	Maximum	1530	nm
Macrobending loss	Radius	30	mm
	Number of turns	100	
	Maximum at 1625 nm	0.50	dB
Proof stress	Minimum	0.69	GPa
Chromatic dispersion parameter	$D_{1550\text{max}}$	20	ps/(nm × km)
	$S_{1550\text{max}}$	0.070	ps/(nm <sup>2</sup> × km)
Uncabled fibre PMD coefficient	Maximum	(Note 2)	
<b>Cable attributes</b>			
<b>Attribute</b>	<b>Detail</b>	<b>Value</b>	<b>Unit</b>
Attenuation coefficient (Note 1)	Maximum at 1550 nm	0.22	dB/km
PMD coefficient (Note 2)	$M$	20	cables
	$Q$	0.01	%
	Maximum $\text{PMD}_Q$	0.20	ps/√km
NOTE 1 – The attenuation coefficient values listed in this table should not be applied to short cables such as jumper cables. For example, [b-IEC 60794-2-11] specifies the attenuation coefficient of indoor cable as 1.0 dB/km or less.			
NOTE 2 – According to clause 7.2, a maximum $\text{PMD}_Q$ value on uncabled fibre is specified in order to support the primary requirement on cable $\text{PMD}_Q$ .			

**Table 4 – ITU-T G.654.D attributes**

<b>Fibre attributes</b>			
<b>Attribute</b>	<b>Detail</b>	<b>Value</b>	<b>Unit</b>
Mode field diameter	Wavelength	1550	nm
	Range of nominal values	11.5-15.0	µm
	Tolerance	±0.7	µm
Cladding diameter	Nominal	125	µm
	Tolerance	±1	µm
Core concentricity error	Maximum	0.8	µm
Cladding non-circularity	Maximum	2.0	%
Cable cut-off wavelength	Maximum	1530	nm
Macrobending loss (Note 4)	Radius	TBD	mm
	Number of turns	TBD	
	Maximum at 1550 nm	TBD	dB
	Radius	30	mm
	Number of turns	100	
	Maximum at 1625 nm	2.0	dB
Proof stress (Note 2)	Minimum	0.69	GPa
Chromatic dispersion parameter	$D_{1550\text{max}}$	23	ps/(nm × km)
	$S_{1550\text{max}}$	0.070	ps/(nm <sup>2</sup> × km)
Uncabled fibre PMD coefficient	Maximum	(Note 3)	
<b>Cable attributes</b>			
<b>Attribute</b>	<b>Detail</b>	<b>Value</b>	<b>Unit</b>
Attenuation coefficient (Note 1)	Maximum at 1550 nm	0.20	dB/km
PMD coefficient (Note 3)	$M$	20	cables
	$Q$	0.01	%
	Maximum $\text{PMD}_Q$	0.20	ps/√km
NOTE 1 – The attenuation coefficient values listed in this table should not be applied to short cables such as jumper cables. For example, [b-IEC 60794-2-11] specifies the attenuation coefficient of indoor cable as 1.0 dB/km or less.			
NOTE 2 – A higher proof stress may be considered depending on the applied system requirements.			
NOTE 3 – According to clause 7.2, a maximum $\text{PMD}_Q$ value on uncabled fibre is specified in order to support the primary requirement on cable $\text{PMD}_Q$ .			
NOTE 4 – Macrobending loss specification at 1550 nm may be useful in some systems. The specification values are to be determined including bending radius and number of turns.			

**Table 5 – ITU-T G.654.E attributes**

<b>Fibre attributes</b>			
<b>Attribute</b>	<b>Detail</b>	<b>Value</b>	<b>Unit</b>
Mode field diameter	Wavelength	1550	nm
	Range of nominal values	11.5-12.5	µm
	Tolerance	±0.7	µm
Cladding diameter	Nominal	125	µm
	Tolerance	±1	µm
Core concentricity error	Maximum	0.8	µm
Cladding non-circularity	Maximum	2.0	%
Cable cut-off wavelength (Note 1)	Maximum	1530	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 (Note 2)	$D_{1550\text{max}}$	23	ps/(nm × km)
	$D_{1550\text{min}}$	17	ps/(nm × km)
	$S_{1550\text{max}}$	0.070	ps/(nm <sup>2</sup> × km)
	$S_{1550\text{min}}$	0.050	ps/(nm <sup>2</sup> × km)
Uncabled fibre PMD coefficient	Maximum	(Note 3)	
<b>Cable attributes</b>			
<b>Attribute</b>	<b>Detail</b>	<b>Value</b>	<b>Unit</b>
Attenuation coefficient (Note 4)	Maximum at 1550 nm	0.23	dB/km
	Maximum at 1530-1 612 nm	0.25	dB/km
	Maximum at 1 612-1625 nm	TBD (Note 5)	dB/km
PMD coefficient (Note 3)	$M$	20	cables
	$Q$	0.01	%
	Maximum PMD $Q$	0.20	ps/√km
NOTE 1 – When ITU-T G.654.E fibre is used at central frequencies for applications specified in [b-ITU-T G.698.2], corresponding to wavelengths in the range between 1527.8 and 1530 nm, then the cable cut-off wavelength should be less than 1527 nm.			
NOTE 2 – From 1530 nm to 1625 nm, chromatic dispersion coefficient $D(\lambda)$ at a given wavelength $\lambda$ can be specified by equation (6-1).			
NOTE 3 – 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 4 – The attenuation coefficient values listed in this table should not be applied to short cables such as jumper cables. For example, [b-IEC 60794-2-11] specifies the attenuation coefficient of indoor cable as 1.0 dB/km or less.			
NOTE 5 – The attenuation increases at these longer wavelengths due to the macro/micro bending after the cabling process/deployment should be taken into account. Typically, an attenuation coefficient of 0.35 dB/km or less from 1612 nm to 1625 nm might be achieved.			

## 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. To estimate statistical link attribute values for attenuation and chromatic dispersion, typical values of optical fibre links are provided in clause I.4. The estimation methods for the 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:

$$A = \alpha L + \alpha_s x + \alpha_{\text{con}} y \quad (\text{I-1})$$

where:

$\alpha$  = mean attenuation coefficient of fibre cables in a link

$\alpha_s$  = mean splice loss

$x$  = number of splices in a link

$\alpha_{\text{con}}$  = 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.). Equation I-1 does not include the loss of equipment connectors. The typical values found in clause I.5 are for the attenuation coefficient of an optical fibre link. 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 picoseconds per nanometre 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 clause I.5. These values, together with link length,  $L_{\text{Link}}$ , can be used to calculate the typical chromatic dispersion for use in optical link design.

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

### I.3 Differential group delay

The DGD 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 cable. 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,  $L_{\text{Ref}}$ : 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,  $L_c$ : 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 for submarine and terrestrial application, respectively, according to clauses I.1 and I.2. The implied fibre induced maximum DGD values in Table I.3 that are related to description in clause I.3 are intended for guidance with regard to the requirement for other optical elements that may be in the link.

**Table I.1 – Representative values of a concatenated optical fibre link for submarine application**

Attribute	Detail	Value
Attenuation coefficient	Wavelength	Typical link value (Note)
	1550 nm	0.25 dB/km
	1625 nm	TBD
Typical chromatic dispersion parameters	$D_{1550}$	TBD
	$S_{1550}$	TBD
NOTE – Typical link value corresponds to the link attenuation coefficient used in [b-ITU-T G.957] and [b-ITU-T G.696.1].		

**Table I.2 – Representative values of a concatenated optical fibre link for terrestrial application**

Attribute	Detail	Value
Attenuation coefficient	Wavelength	Typical link value (Note)
	1550 nm	TBD
	1625 nm	TBD
Typical chromatic dispersion parameters	$D_{1550}$	TBD
	$S_{1550}$	TBD
NOTE – Typical link value corresponds to the link attenuation coefficient used in [b-ITU-T G.957] and [b-ITU-T G.696.1].		

**Table I.3 – Differential group delay**

Maximum PMD <sub>Q</sub> (ps/√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 Gbit Ethernet systems.			

NOTE – Cable section length is 10 km except for the 0.10 ps/km<sup>½</sup>/> 4 000 km link where, if set to 25 km, the probability level is  $6.5 \times 10^{-8}$ .

## I.5 Non-linear coefficient

The effect of chromatic dispersion is interactive with the non-linear coefficient,  $n_2/A_{\text{eff}}$ , where  $A_{\text{eff}}$  denotes effective area, 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. Test methods for the non-linear coefficient remain under study.

## I.6 An example of statistical 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, a limited number of spooled fibres and cables, 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 the fibre or 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:

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

If it is assumed that all cable section lengths are less than some common value,  $L_{\text{Cab}}$ , and simultaneously reducing the number of assumed cable sections to  $M = L_{\text{Link}}/L_c$ , then, for a link comprised of equal-length cables,  $L_i = L_c$ , equation (I-3) becomes

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

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

Once a distribution of the fibre parameter has been established, the Monte Carlo method can be used to determine the probability density,  $f_{\text{Link}}$ , 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 characterize 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 has been computed to produce a high-density histogram of the concatenated distribution of the fibre parameter. If the histogram is used directly without any additional characterization, such as Gaussian fitting, the number of samples should be at least  $10^4$ .

Because of the central limit theorem, the histogram of the statistical values of the fibre parameter in a concatenated cabled link will tend to converge to distributions that can be described with a minimum of two parameters. Hence, the histogram can be fitted to a parametric distribution that enables extrapolation to probability levels that are smaller than those 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 or chromatic dispersion can be interpolated from the associated cumulative probability density function.

It should be noted that the applicability of the methodology used in this example is for further study.

## Bibliography

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