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SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Transmission media characteristics – Optical fibre cables

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

ITU-T Recommendation G.654

(Formerly CCITT Recommendation)

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ITU-T Recommendation G.654

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

Source

ITU-T Recommendation G.654 was revised by ITU-T Study Group 15 (1997-2000) and approved by the World Telecommunication Standardization Assembly (Montreal, 27 September – 6 October 2000).

FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications. The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this Recommendation, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

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As of the date of approval of this Recommendation, ITU had received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementors are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database.

CONTENTS

ITU-T Recommendation G.654

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

1 Scope

This Recommendation describes a single-mode optical fibre which has the zero-dispersion wavelength around 1300 nm wavelength which is loss-minimized and cut-off shifted single-mode optical fibre at a wavelength around 1550 nm and which is optimized for use in the 1500-1600 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 (attenuation, cut-off wavelength, chromatic dispersion and polarization mode dispersion etc.), transmission and mechanical characteristics of this CSF are described below.

Some provisions are made to support transmission at higher wavelengths up to 16xx, with xx less than or equal to 25 nm. 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 they are delivered;
- link attributes that are characteristics of concatenated cables, describing estimation method of system interface parameters, based on measurements, modelling, or other considerations. Some typical link attribute values are given in Appendix I.

The table of recommended values is provided to allow ease of reference. The table indicates the base subcategory of the optical fibre. In accordance with evolution of technology in the future, new subcategories may be created in terms of system implementation.

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]. The characteristic 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 contain provisions which, through reference in this text, constitute provisions of this Recommendation or other relevant information. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; all 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.

2.1 Normative reference

[1] ITU-T G.650 (2000), *Definition and test methods for the relevant parameters of single-mode fibres*.

2.2 Informative references

The following ITU-T Recommendations contain provisions which, through reference in this text, constitute other relevant information.

[2] ITU-T G.663 (2000), *Application related aspects of optical amplifier devices and subsystems.*

[3] ITU-T G.691 (2000), *Optical interfaces for single-channel STM-64, STM-256 and other SDH systems with optical amplifiers.*

[4] ITU-T G.692 (1998), *Optical interfaces for multichannel systems with optical amplifiers.*

3 Terms and definitions

For the purpose of this Recommendation, the definitions given in ITU-T G.650 [1] apply.

Values shall be rounded to the number of digits given in the tables of recommended values before conformance is evaluated.

4 Abbreviations

This Recommendation uses the following abbreviations:

A_{eff}	Effective Area
CSF	Cut-off Shifted Fibre
DGD	Differential Group Delay
GPa	GigaPascal
MFD	Mode Field Diameter
n_2/A_{eff}	Nonlinear coefficient
PMD	Polarization Mode Dispersion
RTM	Reference Test Method
TBD	To Be Determined
WDM	Wavelength Division Multiplexing

5 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 7. 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.

5.1 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 MFD that is specified shall be within the range found in clause 7. The specified tolerance of MFD shall not exceed the value in clause 7. The deviation from nominal shall not exceed the specified tolerance.

5.2 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 7. The cladding deviation from nominal shall not exceed the specified tolerance.

5.3 Core concentricity error

The core concentricity error shall not exceed the value specified in clause 7.

5.4 Non-circularity

5.4.1 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.

5.4.2 Cladding non-circularity

The cladding non-circularity shall not exceed the value found in clause 7.

5.5 Cut-off wavelength

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

a) cable cut-off wavelength λ_{cc};

b) fibre cut-off wavelength λ_c;

c) jumper cable cut-off wavelength λ_{cj}.

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, λ_{cc} and λ_{cj} depends on the specific fibre and cable design and the test conditions. While in general $\lambda_{cc} < \lambda_{cj} < \lambda_c$, 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 can be approached in two alternate ways:

1) recommending λ_c to be less than 1600 nm: when a lower limit is appropriate λ_c should be greater than 1350 nm;

2) recommending the maximum value of λ_{cc} to be 1530 nm.

NOTE 2 – The above values ensure single-mode transmission at around 1550 nm. For WDM applications requiring operation at a wavelength of (1550 nm-x), the above values should be reduced by x nm.

These two specifications need not both be invoked. Since specification of λ_{cc} is a more direct way of ensuring single-mode cable operation, it is the preferred option. When circumstances do not readily permit the specification of λ_{cc} (e.g. in single-mode optical fibre cables such as jumper cables or cables to be deployed in a significantly different manner than in the λ_{cc} RTM), then the specification of λ_c is appropriate.

When the user chooses to specify λ_{cc} as in 2), it should be understood that λ_c may exceed 1600 nm.

When the user chooses to specify λ_c as in 1), then λ_{cc} need not be specified.

In the case where the user chooses to specify λ_{cc}, it may be permitted that λ_c be higher than the minimum operating wavelength relying on the effects of cable fabrication and installation to yield λ_{cc} values below the minimum operating wavelength for the shortest length of cable between two joints.

In the case where the user chooses to specify λ_{cc}, a qualification test may be sufficient to verify that the λ_{cc} requirement is being met.

The cable cut-off wavelength, λ_{cc} shall not exceed the maximum specified in clause 7.

5.6 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 7 for the specified wavelength(s), bend radius, and number of turns.

If the fibre is to be used at wavelength exceeding 1550 nm, the maximum loss at the highest anticipated wavelength may be projected from a loss measurement at 1550 nm, using either spectral loss modelling or a statistical database for that particular fibre design. Alternatively, a qualification test at the longer wavelength may be performed.

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 to implement, it is suggested that not less than 40 turns, and a proportionately smaller loss increase be required.

NOTE 4 – If bending radii smaller than the recommended value are planned to be used in splice cases or elsewhere in the system (for example R = 30 mm), it is suggested that the same maximum loss value shall apply to the same number of turns of fibre deployed with this smaller radius.

NOTE 5 – 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 loss specification of the cabled fibre.

NOTE 6 – In the event that routine tests are required a small diameter loop with one or several turns can be used instead of the recommended test, for accuracy and measurement ease of the 1550 nm bend sensitivity. 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 recommended test and allowed test.

5.7 Material properties of the fibre

5.7.1 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.

5.7.2 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.

5.7.3 Proofstress level

The specified proofstress σ_p shall not be less than the minimum specified in clause 7.

NOTE – The definitions of the mechanical parameters are contained in 1.2 and 2.6/G.650.

5.8 Refractive index profile

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

5.9 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 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 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.

5.10 Chromatic dispersion coefficient

The measured group delay per unit fibre length versus wavelength shall be fitted by the quadratic expression (see ITU-T G.650 [1]):

$$\tau(\lambda) = \tau_{1550} + (S_{1550}/2)(\lambda - 1550)^2 + D_{1550}(\lambda - 1550)$$

Here τ_{1550} is the relative group delay at the wavelength $\lambda = 1550$ nm. The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated quadratic expression:

$$D(\lambda) = S_{1550}(\lambda - 1550) + D_{1550}$$

Here S_{1550} is the (uniform) chromatic dispersion slope at 1550 nm wavelength, i.e. the value of the chromatic dispersion slope $S_{1550}(\lambda) = dD/d\lambda$ at $\lambda = 1550$ nm. Also, D_{1550} denotes the chromatic dispersion values at $\lambda = 1550$ nm.

NOTE 1 – These equations for $\tau(\lambda)$ and $D(\lambda)$ are sufficiently accurate over the 1500-1600 nm range. They are not meant to be used in the 1310 nm region.

NOTE 2 – Alternatively, the chromatic dispersion coefficient can be measured directly, for example by the differential phase shift method. In this case, a straight line $\tau(\lambda)$ shall be fitted directly to the dispersion coefficient for determining S_{1550} and D_{1550}.

5.11 Examples of fibre design guidelines

Appendix II gives an example of fibre design guidelines for the loss-minimized and cut-off shifted fibre (CSF) from KDD, Japan.

6 Cable attributes

Since the geometrical and optical characteristics of fibres given in clause 5 are barely affected by the cabling process, this section 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.

6.1 Attenuation coefficient

The attenuation coefficient is specified with a maximum value at one or more wavelengths in the 1500-1600 nm region. The optical fibre cable attenuation coefficient values shall not exceed the values found in clause 7.

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

6.2 Polarization mode dispersion coefficient

Systems with lower bit rate distance products can tolerate higher values of PMD coefficient without impairment.

Not all tables include requirements on PMD. When required, 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 IEC 61282-3 [IV.1], and are summarized in Appendix III.

The manufacturer shall supply a PMD link design value, 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 PMD_Q. For the values of M and Q given in clause 7, the value of PMD_Q shall not exceed the maximum PMD coefficient specified in clause 7.

Measurements on uncabled fibre can be used to generate cabled fibre statistics when the design and processes are stable and the relationships between the PMD coefficients of uncabled and cabled fibres are known. When such a relationship has been demonstrated, then the cabler may optionally specify a maximum PMD value on the uncabled fibres.

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.

7 Tables of recommended values

Table 1 summarize the recommended values for a number of species of fibres that satisfy the objectives of this Recommendation.

G.654.A is the base subcategory for a cut-off shifted single-mode optical fibre cable. This subcategory is suitable for the systems in ITU-T G.691 [3] and ITU-T G.692 [4] in the 1550 nm wavelength region.

Table 1/G.654 – G.654.A Cable base category

Fibre attributes		
Attribute	**Detail**	**Value**
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
Macrobend loss	Radius	37.5 mm
	Number of turns	100
	Maximum at 1550 nm	0.50 dB
Proof stress	Minimum	0.69 GPa
Chromatic dispersion coefficient	$D_{1550max}$	20 ps/nm·km
	$S_{1550max}$	0.070 ps/nm^2·km
Uncabled fibre PMD coefficient	Maximum	ps/√km (Note)
Cable attributes		
Attenuation coefficient	Wavelength	
	Maximum at 1550 nm	0.22 dB/km
PMD coefficient	M	20 cables
	Q	0.01%
	Maximum PMD_Q	0.5 ps/√km
NOTE – An optional maximum PMD coefficient on uncabled fibre may be specified by cablers to support the primary requirement on cable PMD_Q if it has been demonstrated for a particular cable construction.		

APPENDIX I

Information for link attributes and system design

A concatenated link usually includes a number of spliced factory lengths of optical fibre cable. The requirements for factory lengths are given in clauses 5 and 6. The transmission parameters for concatenated links must take into account not only the performance of the individual cable lengths but also the statistics of concatenation.

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

Link attributes are affected by factors other than optical fibre cables by such things as splices, connectors, and installation. These factors cannot be specified in this Recommendation. For the purpose of link attribute values estimation, typical values of optical fibre cables are provided in the tables below. The estimation methods of parameters needed for system design are based on measurements, modelling or other considerations.

I.1 Attenuation

The attenuation A of a link is given by:

$$A = \alpha L + \alpha_s x + \alpha_c y$$

where

α typical 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 I.5 are for the attenuation coefficient of optical fibre cable 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 5.10).

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. 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 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.

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

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. 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 IEC 61282-3 and are summarized in Appendix IV. 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 IEC 61282-3 [IV.1].

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}.

Clause I.5 contains values for these metrics that are appropriate for optical fibre cable that follows the recommended statistical PMD limits in Tables 2 and 3.

I.4 Nonlinear coefficient

The effect of chromatic dispersion is interactive with the nonlinear coefficient, n_2/A_{eff}, regarding system impairments induced by nonlinear optical effects (see ITU-T G.663 [2]). Typical values vary with the implementation. The test methods for nonlinear coefficient remain under study.

I.5 Tables of common typical values

The values in the following table are representative of concatenated optical fibre cables according to I.1, I.2, and I.3.

Attenuation coefficient	Wavelength	Typical value
	1550 nm	0.25 dB/km
	16XX nm (Note 1)	TBD
Chromatic dispersion coefficient	D_{1550}	TBD
	S_{1550}	TBD
Differential group delay (DGD) (Note 2)	Reference link length	400 km
	Typical maximum cable section length	10 km
	Maximum DGD	25 ps
	Maximum probability	6.5×10^{-8}
NOTE 1 – The maximum wavelength in this band has not been fully determined. XX, however, is less than or equal to 25 nm. NOTE 2 – These values are only appropriate when the cabled PMD_Q values in Table 1 is specified.		

APPENDIX II

Examples of fibre design guideline

In the optical fibre design, the mode field diameter (MFD) 2W and the effective cut-off wavelength λ_{ce} are very important parameters. The equi-bending loss α_b, dispersion D, and refractive index Δ curves of the matched cladding fibre at 1.55 µm wavelength as a function of 2W and λ_{ce} are shown in Figure II.1[1]. Here, the parallelogram area corresponds to a 1.31 µm optimized single-mode optical fibre as recommended by the ITU-T (CCITT) G.652 fibre window ($2W_{1.55 \mu m} = 10 \pm 1.0$ µm, 1.10 µm < λ_{ce} < 1.28 µm). From Figure II.1, it is found that the 1.31 µm optimized single-mode optical fibre (SMF, ITU-T G.652) using a depressed-cladding design is affected significantly by the macrobending loss in the 1.55 µm wavelength region. The cabling loss due to the microbending can be considered as the equivalent to a macrobending loss at equi-bending radius R_e.

The excess loss increase due to the cabling process was about 0.015 dB/km at 1.55 µm wavelength for the single-mode optical fibre ($V \cong 1.7$) and the value corresponds to a bending radius $R_e = 45$ mm. Here, the theoretical microbending loss was calculated by an equivalent macrobending radius of $R_e = 45$ mm.

To preserve the low-loss feature of the optical fibres, the additional loss increase due to cabling process is made as small as possible. From Figure II.1, it is found that, to realize a cabling loss of less than 0.005 dB/km, the upper limit of the mode field diameter (MFD) 2W and lower limit of the effective cut-off wavelength λ_{ce} are about 11.5 µm and 1.35 µm, respectively, and the desirable optimum fibre parameters are shown by the hatched area in Figure II.1. Increasing the effective cut-off wavelength λ_{ce} can improve the microbending resistance at 1.55 µm without increasing the fibre intrinsic loss, however, the upper limit of the effective cut-off wavelength λ_{ce} (up to 1.60 µm) should be determined by considering single-mode operation in the longer cable condition. Here, as an example, it is known that the effective cut-off wavelength difference between the UV-coated fibre (2 m) and long-length cabled fibre (more than 20 km) is about 70 nm.

The points (•) in Figure II.1 represent measurements on 1.55 µm loss-minimized and cut-off shifted single-mode optical fibre (CSF) samples, and their parameters are shown in Table II.1. In Table II.1, Fibres 1 and 2 represent pure-silica core/F-depressed cladding fibre and Fibre 3 and 4 denote slightly Ge and F-doped core/F-depressed cladding fibre, and Fibre 5 is conventional Ge-doped core fibre, respectively. Also, Fibre 6 is conventional 1.31 µm standard single-mode optical fibre (SMF). From Table II.1, it is found that the test fibre loss and chromatic dispersion were 0.176-0.197 dB/km and 17.7-19.3 ps/nm-km, respectively. The Rayleigh scattering coefficients, A_0 and wavelength-independent loss, B_0 of these optical fibres were about 0.83-0.97 dB/km-μm^4 and 0.011-0.015 dB/km, respectively.

The experimental results of the macrobending loss of the 1.55 µm loss-minimized and cut-off shifted fibres (CSF, Fibres 1-5) and 1.31 µm optimized fibre (SMF, Fibre 6) are shown in Figure II.2. From Figure II.2, it was found that the macrobending losses of the 1.55 µm loss-minimized and cut-off shifted fibres (CSF) at 1.55 µm wavelength were smaller than that of the conventional single-mode optical fibre (ITU-T G.652) at a system operating wavelength of 1.31 µm, respectively.

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[1] NAMIHIRA (Y.), HORIUCHI (Y.) and WAKABAYASHI (H.): Optimum fibre parameters of low-loss single-mode optical fibres for use in 1.55 µm wavelength regions, *Electronics Letters*, Vol. 23, No. 18, pp. 963-964, 1987.

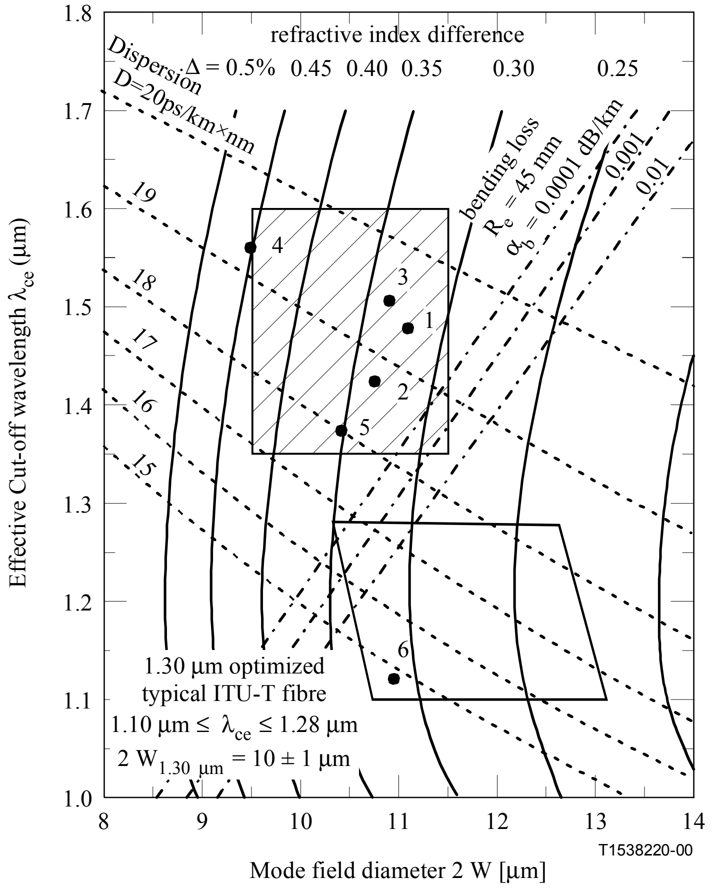
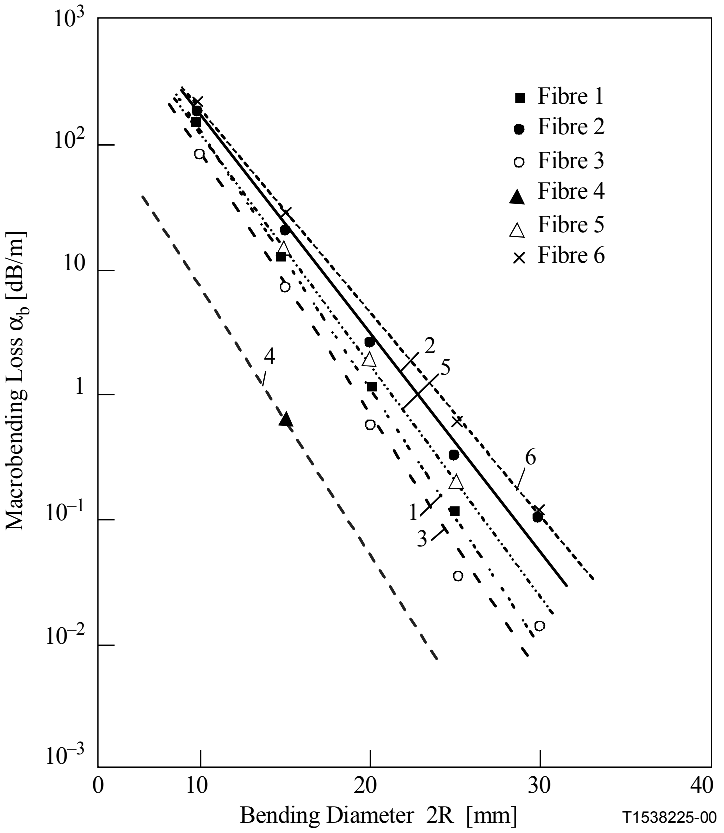


Figure II.1/G.654 – Equibending loss α_b, chromatic dispersion D, and refractive index Δ curves at 1.55 μm wavelength against mode field diameter 2W and effective cut-off wavelength λ_{ce}

Table II.1/G.654 – Fibre parameters for 1.55 μm loss-minimized and cut-off shifted single-mode optical fibres (CSF, ITU-T G.654)

Fibre	MFD [μm] @1.55 μm	λ_{ce} [μm]	Δ [%]	Loss [dB/km] @1.55 μm (@1.30 μm)	Dispersion [ps/nm-km] @1.55 μm (@1.30 μm)
1	11.1	1.48	0.33	0.176 (0.320)	19.27
2	10.8	1.43	0.34	0.184 (0.323)	18.69
3	10.9	1.51	0.35	0.181 (0.348)	18.92
4	9.50	1.56	0.45	0.189 (0.334)	18.99
5	10.1	1.38	0.35	0.197 (0.351)	17.67
Min ~ max	9.50 ~ 11.1	1.38 ~ 1.56	0.33 ~ 0.45	0.176 ~ 0.197 (0.320 ~ 0.351)	17.67 ~ 19.27
Fibres 1 and 2: pure silica core; Fibres 3 and 4: slightly Ge-doped core/F-depressed cladding; Fibre 5: conventional Ge-doped core.					



NOTE – Crosses (broken-line curve) represent Fibre 6, a typical ITU-T (CCITT) G.652 fibre at $\lambda = 1.30\ \mu m$ $(\lambda_{ce} \cong 1.12\ \mu m, 2W_{1.30 \mu m} \cong 9.20, \Delta \cong 0.33\%)$.

Figure II.2/G.654 – Macrobending loss as a function of diameter of curvature of test single-mode optical fibre samples at 1.55 µm

APPENDIX III

Information on polarization mode dispersion statistics

This appendix is provided to summarize some of the statistical calculations for PMD. IEC 61282-3 [IV.1] documents the calculations and theory more completely. This will be given in the following clauses:

III.1 Introduction

III.2 Data collection

III.3 Calculation of PMD_Q (Monte Carlo)

III.4 Calculation for DGD_{max} (Monte Carlo)

NOTE – Other calculation methods are allowed and defined in IEC 61282-3 [IV.1]. The Monte Carlo method is given here because it is the easiest to describe.

III.1 Introduction

Polarization mode dispersion (PMD) is a statistical attribute that, for a given fibre, is defined as the average of measured differential group delay (DGD) values across a range of wavelengths. Since the DGD values are random across time and wavelength, there is a theoretical lower limit to achievable reproducibility of the reported PMD value of approximately ±15%. This feature implies that it is not appropriate to select individual fibres or cables to a specification that is tighter than the capability of the process. Such selections are often appropriate for deterministic attributes like attenuation but are not generally appropriate for PMD. This means that a specification on the overall process distribution is most reasonable.

A second consideration regarding the functionality of PMD is that system impairment at a given time and wavelength is controlled by the DGD value, which varies statistically around the PMD value. If one is given the PMD value for a particular cabled fibre, one can calculate the probability that DGD exceeds a given value. It is clear, however, that application of these formulae to a maximum specified value will yield a very inaccurate view of the actual system performance. A statistical specification on PMD, however, can lead to a statistical boundary on the DGD values for the population as a whole. This boundary, defined in terms of probability, leads to a value for use in system design that is approximately 20% lower in DGD value and two orders of magnitude less in probability than the values that would be obtained without a statistical specification.

From the first consideration, it is desirable to define a single statistical metric for the distribution of the PMD values that are measured on optical fibre cables. The metric therefore must incorporate both aspects of process mean and process variability. An upper confidence limit at some probability level is such a metric.

It is known that the PMD coefficient of a set of concatenated cables can be estimated by the computation of the quadrature average of the PMD coefficients of the individual cables. To give the upper confidence limit metric more meaning in terms of application, the upper bound for a concatenated link of twenty cables is computed. This number of cables is smaller than that used in most links, but is large enough to be meaningful in terms of projecting DGD distributions for concatenated links. A probability value of 0.01% is also standardized – partially on the basis of obtaining equivalence with the probability that DGD exceeds a bound, which is required to be very low. The upper confidence limit is named PMD_Q, or link design value and this specification type is known as Method 1.

The probability limit for DGD is set at $6.5 \cdot 10^{-8}$ based on various system considerations including the presence of other PMD generating components that may be in the links. IEC 61282-3 describes a method of determining a maximum (defined in terms of probability) so that if a distribution passes the Method 1 requirement, the DGD across links comprised of only optical fibre cable will exceed the maximum DGD with a probability less than $6.5 \cdot 10^{-8}$. The DGD_{max} value is established for a broad range of distribution shapes. This DGD_{max} method of specifying the PMD distribution of optical fibre cables is known as Method 2. Methods of combining the Method 2 parameters with those of other optical components are given in IEC 61282-3.

Method 1 is a metric that is based on what is measured and is therefore somewhat more straightforward for use in trade and commerce as a normative requirement. Method 2 is a means of extrapolating the implications for system design and is therefore included as information for system design.

III.2 Data collection

The calculations are done with PMD values that are representative of a given cable construction and manufacturing time period. Typically at least 100 values are required. The sample is normally taken on different production cables and different fibre locations within.

The cable distribution can be augmented by measurements of uncabled fibre provided that a stable relationship between uncabled fibre and cable values has been demonstrated for a given construction. One means of such augmentation is to generate several possible cable values from the value of each uncabled fibre. These different values should be selected randomly to represent both the usual relationship and the variability that follows from, for example, measurement reproducibility. Because the range of variations includes reproducibility error, this method of estimating the distribution of cable PMD values can lead to over-estimation of PMD_Q.

The length of the samples measured could seem to have implications on the Method 2 deductions. This has been studied – with the following conclusions. The Method 2 implications remain valid for any link less than 400 km as long as either:

- the installed cables are less than 10 km; or
- the measured lengths are less than 10 km.

III.3 Calculation of PMD_Q (Monte Carlo)

Other methods of calculation are given in IEC 61282-3. The Monte Carlo method is described here because it is the easiest to describe and uses the fewest assumptions.

The measured PMD coefficient values are represented by x_i, with i ranging from 1 to N, the number of measurements. These values will be used to generate 100 000 concatenated link PMD coefficient values, each computed with the quadrature average of 20 individual cable values that are randomly selected from the sample population.

NOTE – When N = 100, there are $5.3 \cdot 10^{20}$ possible link values.

For each link value computation, select 20 random numbers between 1 and N. Select these values and note them with index, k. The link PMD coefficient, y, is calculated as:

$$y = \left(\frac{1}{20} \sum_{k=1}^{20} x_k^2 \right)^{1/2} \tag{III-1}$$

Collect the 100 000 values of y into a high density histogram as they are being computed. When this computation is complete, calculate the cumulative probability function from the histogram and determine the PMD value associated with the 99.99% level. Report this value as PMD_Q. If the computed PMD_Q is less than the specified value {0.5 ps/sqrt(km)}, the distribution passes Method 1.

III.4 Calculation for DGD_{max} (Monte Carlo)

This calculation builds on that of the calculation for PMD_Q. In this calculation, a value of DGD_{max} is predefined (at 25 ps) and a probability of exceeding this value, P_F, is calculated. If the computed probability is less than the specified value ($6.5 \cdot 10^{-8}$), the distribution passes Method 2.

Before beginning the Monte Carlo, calculate the PMD coefficient limit, P_{max}, as:

$$P_{\max} = \frac{DGD_{\max}}{\sqrt{L_{ref}}} = \frac{25}{20} = 1.25$$

For each subsequent pair of 20 cable link concatenation values, y_{2j-1} and y_{2j}, a 40 cable concatenation value, z_j, is generated as:

$$z_j = \left(\frac{y_{2j-1}^2 + y_{2j}^2}{2} \right)^{1/2} \tag{III-2}$$

NOTE – This yields 50 000 values of z_j, an adequate number.

Calculate the probability of exceeding DGD$_{\max}$ on the jth concatenation of 40 links, p$_j$, as

$$p_j = 1 - \int_0^{P_{\max}/z_j} 2\left(\frac{4}{\pi}\right)^{3/2} \frac{t^2}{\Gamma(3/2)} \exp\left[-\frac{4}{\pi}t^2\right] dt \qquad \text{(III-3)}$$

Excell$^{\text{TM}}$ defines a function that can compute p$_j$, GAMMADIST (X, ALPHA, BETA, Cumulative). The call to this function should be:

$$PJ = 1 - GAMMADIST(4 * PMAX * PMAX / (PI() * ZI * ZI), 1.5, 1, TRUE) \qquad \text{(III-4)}$$

The probability of exceeding DGD$_{\max}$, P$_F$, is given as:

$$P_F = \frac{1}{50000} \sum_j p_j \qquad \text{(III-5)}$$

If P$_F$ is less than the specified value, the distribution passes Method 2.

APPENDIX IV

Bibliography

[IV.1] IEC 61282-3:(work in progress), Guidelines for the Calculation of PMD in Fibre Optic Systems.

[IV.2] IEC 60793-2 (86A/563/CDV), *Optical fibres – Part 2: Product specifications*

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