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

Transmission media and optical systems characteristics – Optical fibre cables

Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable

Recommendation ITU-T G.650.1

ITU-T

ITU-T G-SERIES RECOMMENDATIONS

TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

INTERNATIONAL TELEPHONE CONNECTIONS AND CIRCUITS	G.100–G.199
GENERAL CHARACTERISTICS COMMON TO ALL ANALOGUE CARRIER-TRANSMISSION SYSTEMS	G.200–G.299
INDIVIDUAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON METALLIC LINES	G.300–G.399
GENERAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON RADIO-RELAY OR SATELLITE LINKS AND INTERCONNECTION WITH METALLIC LINES	G.400–G.449
COORDINATION OF RADIOTELEPHONY AND LINE TELEPHONY	G.450–G.499
TRANSMISSION MEDIA AND OPTICAL SYSTEMS CHARACTERISTICS	G.600–G.699
General	G.600–G.609
Symmetric cable pairs	G.610–G.619
Land coaxial cable pairs	G.620–G.629
Submarine cables	G.630–G.639
Free space optical systems	G.640–G.649
Optical fibre cables	**G.650–G.659**
Characteristics of optical components and subsystems	G.660–G.679
Characteristics of optical systems	G.680–G.699
DIGITAL TERMINAL EQUIPMENTS	G.700–G.799
DIGITAL NETWORKS	G.800–G.899
DIGITAL SECTIONS AND DIGITAL LINE SYSTEM	G.900–G.999
MULTIMEDIA QUALITY OF SERVICE AND PERFORMANCE – GENERIC AND USER-RELATED ASPECTS	G.1000–G.1999
TRANSMISSION MEDIA CHARACTERISTICS	G.6000–G.6999
DATA OVER TRANSPORT – GENERIC ASPECTS	G.7000–G.7999
PACKET OVER TRANSPORT ASPECTS	G.8000–G.8999
ACCESS NETWORKS	G.9000–G.9999

For further details, please refer to the list of ITU-T Recommendations.

Recommendation ITU-T G.650.1

Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable

Summary

Recommendation ITU-T G.650.1 contains definitions of the linear, deterministic parameters of single-mode optical fibres and cables. It also contains both, reference test methods and alternative test methods for characterizing these parameters.

These test methods are suitable mainly for factory measurements of the linear, deterministic attributes of single-mode fibres and cables. Some of the test methods may also be used to characterize discrete optical components.

History

1993 Definitions and test methods were removed from single-mode fibre Recommendations such as Recommendation ITU-T G.652 and used to create the initial version of Recommendation ITU-T G.650.

1997 The second version of Recommendation ITU-T G.650 added definitions and test methods for polarization mode dispersion and Appendices I, II and III. The improved determination of cut-off wavelength (now clause 5.3.1.3.4) was also added.

2000 The third version established reference and alternative test methods for polarization mode dispersion, modified the definitions and test methods for core concentricity error (clauses 3.4 and 5.2), and added clause 5.1.4 and Appendices IV, V and VI.

2002 In order to facilitate maintenance, Recommendation ITU-T G.650 was divided into smaller Recommendations. Recommendation ITU-T G.650.2 contains definitions and test methods for statistical and non-linear attributes of single-mode fibre and cable.

2004 The second version of Recommendation ITU-T G.650.1 added a third alternative test method "Spectral attenuation modelling" (clause 5.4.4) and new Appendix III "Example of a matrix model". This material has been moved from the single-mode fibre Recommendations into this Recommendation G.650.1. In addition, chromatic dispersion fitting procedures have been added (Annex A).

2010 The third version of Recommendation ITU-T G.650.1 added the test method "Test methods for the macrobend loss" (clause 5.6). Jumper cut-off wavelength has been deleted from clause 5.3. Additional description has been added in cut-off wavelength test method (clause 5.3.1.3.2). Corrected Equation 5-1. Detailed description has been added in prooftest method (clause 5.7). Appendix II has been updated.

FOREWORD

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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.

Compliance with this Recommendation is voluntary. However, the Recommendation may contain certain mandatory provisions (to ensure e.g., interoperability or applicability) and compliance with the Recommendation is achieved when all of these mandatory provisions are met. The words "shall" or some other obligatory language such as "must" and the negative equivalents are used to express requirements. The use of such words does not suggest that compliance with the Recommendation is required of any party.

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As of the date of approval of this Recommendation, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementers are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database at http://www.itu.int/ITU-T/ipr/.

CONTENTS

Recommendation ITU-T G.650.1

Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable

1 Scope

This Recommendation contains definitions and test methods suitable mainly for factory measurements of the linear, deterministic attributes of the single-mode optical fibres and cables described in [ITU-T G.652], [ITU-T G.653], [ITU-T G.654], [ITU-T G.655], [ITU-T G.656] and [ITU-T G.657]. These definitions and test methods are generally not appropriate for multimode fibre, such as specified in [ITU-T G.651.1]. Some of the test methods, when so indicated, may also be used to characterize discrete optical components, such as those described in [ITU-T G.671]. [ITU-T G.650.2] contains definitions and test methods for statistical and non-linear attributes.

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.650.2]	Recommendation ITU-T G.650.2 (2007), *Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable.*
[ITU-T G.651.1]	Recommendation ITU-T G.651.1 (2007), *Characteristics of a 50/125 µm multimode graded index optical fibre cable for the optical access network.*
[ITU-T G.652]	Recommendation ITU-T G.652 (2009), *Characteristics of a single-mode optical fibre and cable.*
[ITU-T G.653]	Recommendation ITU-T G.653 (2010), *Characteristics of a dispersion-shifted single-mode optical fibre and cable.*
[ITU-T G.654]	Recommendation ITU-T G.654 (2010), *Characteristics of a cut-off shifted single-mode optical fibre and cable.*
[ITU-T G.655]	Recommendation ITU-T G.655 (2009), *Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable.*
[ITU-T G.656]	Recommendation ITU-T G.656 (2010), *Characteristics of a fibre and cable with non-zero dispersion for wideband optical transport.*
[ITU-T G.657]	Recommendation ITU-T G.657 (2009), *Characteristics of a bending-loss insensitive single-mode optical fibre and cable for the access network.*
[ITU-T G.671]	Recommendation ITU-T G.671 (2002), *Transmission characteristics of optical components and subsystems.*
[IEC 60793-1-30]	IEC 60793-1-30 (2010), *Optical fibres – Part 1-30: Measurement methods and test procedures – Fibre proof test.*
[IEC 60793-1-42]	IEC 60793-1-42 (2007), *Optical fibres – Part 1-42: Measurement methods and test procedures – Chromatic dispersion. Annex C, Differential phase shift test method.*

[IEC 60793-1-44] IEC 60793-1-44 (2001), *Optical fibres – Part 1-44: Measurement methods and test procedures – Cut-off wavelength.*

[IEC 60793-1-45] IEC 60793-1-45 (2001), *Optical fibres – Part 1-45: Measurement methods and test procedures – Mode field diameter.*

[IEC 60793-1-46] IEC 60793-1-46 (2001), *Optical fibres – Part 1-46: Measurement methods and test procedures – Monitoring of changes in optical transmittance.*

[IEC 60793-1-47] IEC 60793-1-47 (2009), *Optical fibres – Part 1-47: Measurement methods and test procedures – Macrobending loss.*

[IEC 61745] IEC 61745 (1998), *End-face image analysis procedure for the calibration of optical fibre geometry test sets.*

[IEC 61746-1] IEC 61746-1 (2009), *Calibration of optical time-domain reflectometers (OTDR) – Part 1: OTDR for single mode fibres.*

3 Definitions

This Recommendation defines the following terms:

3.1 General definitions

3.1.1 refractive index profile: The refractive index along a diameter of the fibre.

3.1.2 reference test method (RTM): A test method in which a characteristic of a specified class of optical fibres or optical fibre cables is measured strictly according to the definition of this characteristic and which gives results which are accurate, reproducible and relatable to practical use.

3.1.3 alternative test method (ATM): A test method in which a given characteristic of a specified class of optical fibres or optical fibre cables is measured in a manner consistent with the definition of this characteristic and gives results which are reproducible and relatable to the reference test method and to practical use.

3.1.4 cladding mode stripper: A device that encourages the conversion of cladding modes to radiation modes.

3.1.5 mode filter: A device designed to accept or reject a certain mode or modes.

3.2 Mechanical characteristics

3.2.1 primary coating: The one or more layers of protective coating material applied to the fibre cladding during or after the drawing process to preserve the integrity of the cladding surface and to give a minimum amount of required protection (e.g., a 250 µm protective coating).

3.2.2 secondary coating: The one or more layers of coating material applied over one or more primary coated fibres in order to give additional required protection or to arrange fibres together in a particular structure (e.g., a 900 µm "buffer" coating, "tight jacket", or a ribbon coating).

3.2.3 prooftest level: The prooftest level is the specified value of tensile stress or strain to which a full length of fibre is subjected for a specified short time period. This is usually done sequentially along the fibre length.

3.2.4 stress corrosion parameter: The stress corrosion (susceptibility) parameter n is a dimensionless coefficient empirically related to the dependence of crack growth on applied stress. It depends upon the ambient temperature, humidity and other environmental conditions.

Both a static and a dynamic value for this parameter can be given.

The static value n_s is the negative of the slope of a static fatigue log-log plot of failure time versus applied stress.

The dynamic value is n_d where $1/(n_d + 1)$ is the slope of a dynamic fatigue log-log plot of failure stress versus applied stress rate.

NOTE – n need not be an integer.

3.3 Mode field characteristics

3.3.1 mode field: The mode field is the single-mode field distribution of the LP_{01} mode giving rise to a spatial intensity distribution in the fibre.

3.3.2 mode field diameter: The mode field diameter (MFD) $2w$ represents a measure of the transverse extent of the electromagnetic field intensity of the mode in a fibre cross-section, and it is defined from the far-field intensity distribution $F^2(\theta)$, θ being the far-field angle, through the following equation:

$$2w = \frac{\lambda}{\pi}\left[\frac{2\int_0^{\frac{\pi}{2}} F^2(\theta)\sin\theta\cos\theta d\theta}{\int_0^{\frac{\pi}{2}} F^2(\theta)\sin^3\theta\cos\theta d\theta}\right]^{\frac{1}{2}} \tag{3-1}$$

3.3.3 mode field centre: The mode field centre is the position of the centroid of the spatial intensity distribution in the fibre.

NOTE 1 – The centroid is located at r_c and is the normalized intensity-weighted integral of the position vector r.

$$r_c = \frac{\iint_{Area} rI(r)dA}{\iint_{Area} I(r)dA} \tag{3-2}$$

NOTE 2 – The correspondence between the position of the centroid, as defined, and the position of the maximum of the spatial intensity distribution requires further study.

3.3.4 mode field concentricity error: The distance between the mode field centre and the cladding centre.

3.3.5 mode field non-circularity: Since it is not normally necessary to measure mode field non-circularity for acceptance purposes, a definition of mode field non-circularity is not necessary in this context.

3.4 Glass geometry characteristics

3.4.1 cladding: The outermost region of glass in the fibre cross-section.

3.4.2 cladding centre: The cladding centre is the centre of a circle which best fits the cladding boundary.

NOTE – The method of best fitting has to be specified.

3.4.3 cladding diameter: The diameter of the circle defining the cladding centre.

3.4.4 cladding diameter deviation: The difference between the actual and the nominal values of the cladding diameter.

3.4.5 cladding tolerance field: For a cross-section of an optical fibre, it is the region between the circle circumscribing the outer limit of the cladding, and the largest circle, concentric with the first one, that fits into the outer limit of the cladding. Both circles shall have the same centre as the cladding.

3.4.6 cladding non-circularity: The difference between the diameters of the two circles defined by the cladding tolerance field, divided by the cladding diameter.

3.4.7 core centre: The core centre is the centre of a circle which best fits the points at a constant level in the near-field intensity pattern emitted from the central region of the fibre, using wavelengths above and/or below the fibre's cut-off wavelength.

NOTE 1 – The above constant level shall be chosen between 5% and 50% of maximum near-field intensity.

NOTE 2 – Usually, the core centre represents a good approximation of the mode field centre.

3.4.8 core concentricity error: The distance between the core centre and the cladding centre.

3.5 Chromatic dispersion definitions

3.5.1 chromatic dispersion: The spreading of a light pulse in an optical fibre caused by the different group velocities of the different wavelengths composing the source spectrum.

3.5.2 group delay: The time required for a light pulse to travel a unit length of fibre. The group delay as a function of wavelength is denoted by $\tau(\lambda)$. It is usually expressed in ps/km.

3.5.3 chromatic dispersion coefficient: Change of the group delay of a light pulse for a unit fibre length caused by a unit wavelength change. Thus, the chromatic dispersion coefficient is $D(\lambda) = d\tau/d\lambda$. It is usually expressed in ps/nm × km.

3.5.4 chromatic dispersion slope: The slope of the chromatic dispersion coefficient versus wavelength curve. The dispersion slope is defined as $S(\lambda) = dD/d\lambda$.

3.5.5 zero-dispersion wavelength: The wavelength at which the chromatic dispersion vanishes.

3.5.6 zero-dispersion slope: The chromatic dispersion slope at the zero-dispersion wavelength.

3.6 Other characteristics

3.6.1 cut-off wavelength: Theoretical cut-off wavelength is the shortest wavelength at which a single mode can propagate in a single-mode fibre. This parameter can be computed from the refractive index profile of the fibre. At wavelengths below the theoretical cut-off wavelength, several modes propagate and the fibre is no longer single-mode but multimode.

In optical fibres, the change from multimode to single-mode behaviour does not occur at an isolated wavelength, but rather smoothly over a range of wavelengths. Consequently, for determining fibre performance in a telecommunication network, theoretical cut-off wavelength is less useful than the actual threshold wavelength for single-mode performance when the fibre is in operation. Thus, a more effective parameter called cut-off wavelength shall be introduced for single-mode fibre specifications as defined in the following:

Cut-off wavelength is defined as the wavelength greater than which the radio between the total power, including launched higher order modes, and the fundamental mode power has decreased to less than 0.1 dB. According to this definition, the second order (LP_{11}) mode undergoes 19.3 dB more attenuation than the fundamental (LP_{01}) mode when the modes are equally excited.

Because cut-off wavelength depends on the length and bends of the fibre, as well as its strain condition, the resulting value of cut-off wavelength depends on whether the measured fibre is configured in a deployed cabled condition, or whether the fibre is short and uncabled. Consequently, there are two types of cut-off wavelength defined: **cable cut-off wavelength** and **fibre cut-off wavelength**.

cable cut-off wavelength λ_{cc} – Cable cut-off wavelength is measured prior to installation on a substantially straight 22 m cable length prepared by exposing 1 m of primary-coated fibre at either end, the exposed ends each incorporating a 40 mm radius loop. Alternatively, this parameter may be measured on 22 m of primary-coated uncabled fibre loosely constrained in loops > 140 mm radius, incorporating a 40 mm radius loop at either end.

Alternative configurations may be used if the empirical results are demonstrated to be either equivalent within 10 nm, or greater than those achieved with the sample configurations. For example, two 40 mm radius loops in a two-metre length of uncabled fibre meets this equivalent criterion for some fibre and cable designs.

fibre cut-off wavelength λ_c – Fibre cut-off wavelength is measured on uncabled primary-coated fibre in the following configuration: 2 metres, with one loop of 140 mm radius (or an equivalent, e.g., split mandrel) loosely constrained with the rest of the fibre kept essentially straight.

To avoid modal noise and dispersion penalties, the cut-off wavelength λ_{cc} of the shortest cable length (including repair lengths when present) should be less than the lowest anticipated system wavelength, λ_s:

$$\lambda_{cc} < \lambda_s \tag{3-3}$$

This ensures that each individual cable section is sufficiently single mode. Any joint that is not perfect will create some higher order (LP_{11}) mode power, and single-mode fibres typically support this mode for a short distance (of the order of metres, depending on the deployment conditions). A minimum distance must therefore be specified between joints in order to give the fibre sufficient distance to attenuate the LP_{11} mode before it reaches the next joint. If inequality (3-3) is satisfied in the shortest cable section, it will be automatically satisfied in all longer cable sections, and single-mode system operation will occur regardless of the elementary section length.

Fibre cut-off wavelength and mode field diameter can be combined to estimate a fibre's bend sensitivity. High fibre cut-off and a small mode field diameter result in a more bend-resistant fibre. This explains why it is often desirable to specify higher values of cut-off wavelength λ_c, even if the upper limit of this parameter exceeds the operating wavelength. All practical installation techniques and cable designs will ensure a cable cut-off wavelength below the operating wavelength.

Since specification of cable cut-off wavelength, λ_{cc}, is a more direct way of ensuring single-mode cable operation, specifying this is preferred to specifying fibre cut-off wavelength, λ_c. However, when circumstances do not readily permit the specification of λ_{cc} (e.g., in single-fibre cable such as pigtails, jumpers or cables to be deployed in a significantly different manner than in the λ_{cc} RTM), then specifying an upper limit for λ_c is appropriate. This option is addressed in [ITU-T G.652], [ITU-T G.653], [ITU-T G.654], [ITU-T G.655], [ITU-T G.656] and [ITU-T G.657].

3.6.2 attenuation: The attenuation $A(\lambda)$ at wavelength λ between two cross-sections 1 and 2 separated by distance L of a fibre is defined, as:

$$A(\lambda) = 10 \log \frac{P_1(\lambda)}{P_2(\lambda)} (\mathrm{dB}) \tag{3-4}$$

where $P_1(\lambda)$ is the optical power traversing the cross-section 1, and $P_2(\lambda)$ is the optical power traversing the cross-section 2 at the wavelength λ.

For a uniform fibre, it is possible to define an attenuation per unit length, or an attenuation coefficient which is independent of the length of the fibre:

$$a(\lambda) = \frac{A(\lambda)}{L} (\mathrm{dB/unit\ length}) \tag{3-5}$$

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations:

ATM	Alternative Test Method
DGD	Differential Group Delay
DWDM	Dense Wavelength Division Multiplexing
ECL	External Cavity Laser
FWHM	Full Width at Half Maximum
Gpa	GigaPascal
LD	Laser Diode
LED	Light Emitting Diode
MFCE	Mode Field Concentricity Error
MFD	Mode Field Diameter
NFP	Near-Field Pattern
OTDR	Optical Time Domain Reflectometer
PMD	Polarization Mode Dispersion
PS	Poincaré-Sphere
PSP	Principal State of Polarization
RTM	Reference Test Method
SOP	State of Polarization
TBD	To Be Determined
WDM	Wavelength Division Multiplexing

5 Test methods

Both reference test method (RTM) and alternative test methods (ATMs) are usually given here for each parameter, and it is the intention that both the RTM and the ATM(s) may be suitable for normal product acceptance purposes. However, when using an ATM, should any discrepancy arise, it is recommended that the RTM be employed as the technique for providing the definitive measurement results.

NOTE – The apparatus and procedure given cover only the essential basic features of the test methods. It is assumed that the detailed instrumentation will incorporate all necessary measures to ensure stability, noise elimination, signal-to-noise ratio, etc.

5.1 Test methods for the mode field diameter

5.1.1 Reference test method: The far-field scan

5.1.1.1 General

The mode field diameter is determined from the far-field intensity distribution $F^2(\theta)$, according to the definition given in clause 3.3.2. The integration limits are shown to be 0 and $\pi/2$, but it is understood that this notation implies the truncation of the integrals in the limit of increasing argument. While the maximum physical value of the argument θ is $\pi/2$, the integrands rapidly approach zero before this value is reached. The relative error in the determination of the mode field diameter, introduced by this truncation, is discussed in clause 5.1.1.2.6.

5.1.1.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure 1.

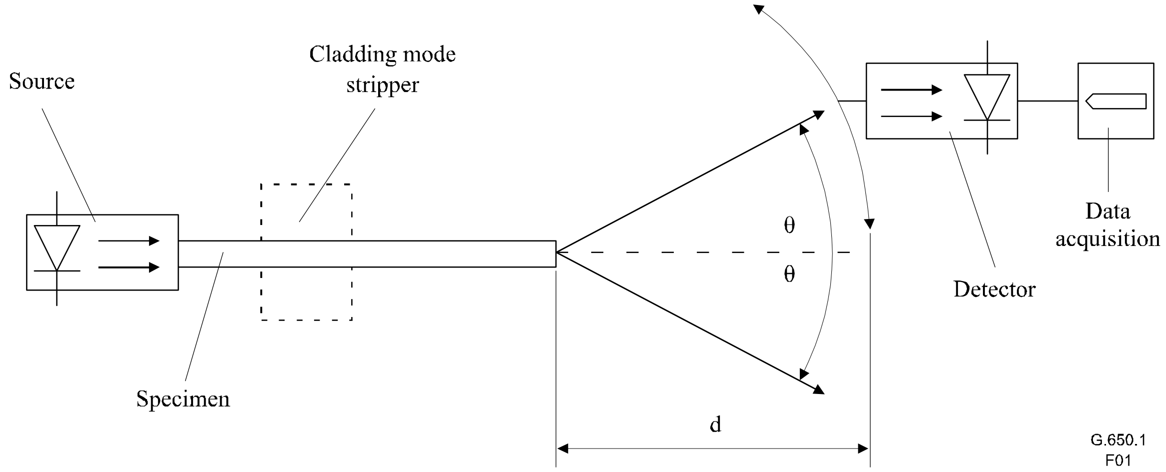


Figure 1 – Typical arrangement of the far-field scan set-up

5.1.1.2.1 Light source

The light source shall be stable in position, intensity and wavelength over a time period sufficiently long to complete the measurement procedure. The spectral characteristics of the source should be chosen to preclude multimode operation. The FWHM spectral width shall be no greater than 10 nm.

5.1.1.2.2 Modulation

It is customary to modulate the light source in order to improve the signal/noise ratio at the receiver. If such a procedure is adopted, the detector should be linked to a signal processing system synchronous with the source modulation frequency. The detecting system should have substantially linear sensitivity characteristics.

5.1.1.2.3 Launching conditions

The launching conditions used must be sufficient to excite the fundamental (LP_{01}) mode. For example, suitable launching techniques could be:

a) jointing with a fibre;

b) launching with a suitable system of optics.

Care should be taken that higher order modes do not propagate. For this purpose, it may be necessary to introduce a loop of suitable radius or another mode filter in order to remove higher order modes.

5.1.1.2.4 Cladding mode stripper

Precautions shall be taken to prevent the propagation and detection of cladding modes.

5.1.1.2.5 Specimen

The specimen shall be a short length of the optical fibre to be measured. Primary fibre coating shall be removed from the section of the fibre inserted in the mode stripper, if used. The fibre ends shall be clean, smooth and perpendicular to the fibre axes. It is recommended that the end faces be flat and perpendicular to the fibre axes to within 1°.

5.1.1.2.6 Scan apparatus

A mechanism to scan the far-field intensity distribution shall be used (for example, a scanning photodetector with pinhole aperture or a scanning pig-tailed photodetector). The detector should be at least 10 mm from the fibre end, and the detector's active area should not subtend too large an angle in the far field. This can be assured by placing the detector at a distance from the fibre end greater than 40 wb/λ, where $2w$ is the expected mode field diameter of the fibre to be measured and b is the diameter of the active area of the detector.

The minimum dynamic range of the measurement should be 50 dB. This corresponds to a maximum scan half-angle of 20° and 25°, or greater, for fibres covered by [ITU-T G.652] and [ITU-T G.653], respectively.

NOTE 1 – Reducing such dynamic range (or maximum scan half-angle) requirements may introduce errors. For example, restricting those values to 30 dB and 12.5° for ITU-T G.652 fibres, and to 40 dB and 20° for ITU-T G.653 fibres, may result in a relative error, in the determination of the MFD, greater than 1%.

NOTE 2 – For ITU-T G.654 fibres, the same considerations as for ITU-T G.652 fibres apply.

5.1.1.2.7 Detector

A suitable detector shall be used. The detector must have linear sensitivity characteristics.

5.1.1.2.8 Amplifier

An amplifier should be employed in order to increase the signal level.

5.1.1.2.9 Data acquisition

The measured signal level shall be recorded and suitably processed.

5.1.1.3 Measurement procedure

The launch end of the fibre shall be aligned with the launch beam, and the output end of the fibre shall be aligned to the appropriate output device.

The following procedure shall be followed: by scanning the detector in fixed steps no greater than 0.5°, the far-field intensity distribution, $F^2(\theta)$, is measured, and the mode field diameter is calculated from Equation 3-1.

5.1.1.4 Presentation of the results

a) Test set-up arrangement, dynamic range of the measurement system, processing algorithms, and a description of the scanning device used (including the scan angle).

b) Launching conditions.

c) Wavelength and spectral linewidth FWHM of the source.

d) Fibre identification and length.

e) Type of cladding mode stripper.

f) Type and dimensions of the detector.

g) Temperature of the sample and environmental conditions (when necessary).

h) Indication of the accuracy and repeatability.

i) Mode field diameter.

5.1.2 First alternative test method: The variable aperture technique

5.1.2.1 General

The mode field diameter is determined from the complementary aperture transmission function a(x), (x = D·tan θ being the aperture radius, and D the distance between the aperture and the fibre):

$$2w = (\lambda/\pi D)\left[\int_0^{\infty} a(x)\frac{x}{(x^2+D^2)^2}\,dx\right]^{1/2} \quad (5\text{-}1)$$

The mathematical equivalence of equations 3-1 and 5-1 is valid in the approximation of small angles θ. Under this approximation, Equation 5-1 can be derived from Equation 3-1 by integration.

5.1.2.2 Test apparatus

5.1.2.2.1 Light source (as in clause 5.1.1.2.1)

5.1.2.2.2 Modulation (as in clause 5.1.1.2.2)

5.1.2.2.3 Launching conditions (as in clause 5.1.1.2.3)

5.1.2.2.4 Cladding mode stripper (as in clause 5.1.1.2.4)

5.1.2.2.5 Specimen (as in clause 5.1.1.2.5)

5.1.2.2.6 Aperture apparatus

A mechanism containing at least twelve apertures spanning the half-angle range of numerical apertures from 0.02 to 0.25 (0.4 for fibres covered by [ITU-T G.653]) should be used. Light transmitted by the aperture is collected and focused onto the detector.

NOTE – The NA of the collecting optics must be large enough not to affect the measurement results.

5.1.2.2.7 Detector (as in clause 5.1.1.2.7)

5.1.2.2.8 Amplifier (as in clause 5.1.1.2.8)

5.1.2.2.9 Data acquisition (as in clause 5.1.1.2.9)

5.1.2.3 Measurement procedure

The launch end of the fibre shall be aligned with the launch beam, and the output end of the fibre shall be aligned to the appropriate output device.

The following procedure shall be followed: the power transmitted by each aperture, P(x), is measured, and the complementary aperture transmission function, a(x), is found as:

$$a(x) = 1 - \frac{P(x)}{P_{\max}} \tag{5-2}$$

where $P_{\max}$ is the power transmitted by the largest aperture and x is the aperture radius. The mode field diameter is computed from Equation 5-1.

5.1.2.4 Presentation of the results

The following details shall be presented:

a) Test set-up arrangement, dynamic range of the measurement system, processing algorithms, and a description of the aperture assembly used (including the NA).

b) Launching conditions.

c) Wavelength and spectral linewidth FWHM of the source.

d) Fibre identification and length.

e) Type of cladding mode stripper.

f) Type and dimensions of the detector.

g) Temperature of the sample and environmental conditions (when necessary).

h) Indication of the accuracy and repeatability.

i) Mode field diameter.

5.1.3 Second alternative test method: The near-field scan

5.1.3.1 General

The mode field diameter is determined from the near-field intensity distribution $f^2(r)$ (r being the radial coordinate):

$$2w = 2\left[2\frac{\int_0^\infty rf^2(r)dr}{\int_0^\infty r\left[\frac{df(r)}{dr}\right]^2 dr}\right]^{1/2} \tag{5-3}$$

The mathematical equivalence of Equations 3-1 and 5-3 is valid in the approximation of small angles θ. Under this approximation, the near-field f(r) and the far-field F(θ) form a Hankel pair. By means of the Hankel transform, it is possible to pass from Equation 3-1 to Equation 5-3 and vice versa.

5.1.3.2 Test apparatus

5.1.3.2.1 Light source (as in clause 5.1.1.2.1)

5.1.3.2.2 Modulation (as in clause 5.1.1.2.2)

5.1.3.2.3 Launching conditions (as in clause 5.1.1.2.3)

5.1.3.2.4 Cladding mode stripper (as in clause 5.1.1.2.4)

5.1.3.2.5 Specimen (as in clause 5.1.1.2.5)

5.1.3.2.6 Scan apparatus

Magnifying optics (e.g., a microscope objective) shall be employed to enlarge and focus an image of the fibre near-field onto the plane of a scanning detector (for example, a scanning photodetector with a pinhole aperture or a scanning pig-tailed photodetector). The numerical aperture and magnification shall be selected to be compatible with the desired spatial resolution. For calibration, the magnification of the optics should have been measured by scanning the length of a specimen whose dimensions are independently known with sufficient accuracy.

5.1.3.2.7 Detector (as in clause 5.1.1.2.7)

5.1.3.2.8 Amplifier (as in clause 5.1.1.2.8)

5.1.3.2.9 Data acquisition (as in clause 5.1.1.2.9)

5.1.3.3 Measurement procedure

The launch end of the fibre shall be aligned with the launch beam, and the output end of the fibre shall be aligned to the appropriate output device.

The following procedure shall be followed: the near-field of the fibre is enlarged by the magnifying optics and focused onto the plane of the detector. The focusing shall be performed with maximum accuracy in order to reduce dimensional errors due to the scanning of a defocused image. The near-field intensity distribution, $f^2(r)$, is scanned and the mode field diameter is calculated from Equation 5-3. Alternatively, the near-field intensity distribution $f^2(r)$ may be transformed into the far-field domain using a Hankel transform and the resulting transformed far-field $F^2(\theta)$ may be used to compute the mode field diameter from Equation 3-1.

NOTE – Discriminate between the radial coordinate r in the fibre end face and the radial coordinate Mr of the scanning detector in the image plane, where M is the magnification.

5.1.3.4 Presentation of the results

a) Test set-up arrangement, dynamic range of the measurement system, processing algorithms, and a description of the imaging and scanning devices used.

b) Launching conditions.

c) Wavelength and spectral linewidth FWHM of the source.

d) Fibre identification and length.

e) Type of cladding mode stripper.

f) Magnification of the apparatus.

g) Type and dimensions of the detector.

h) Temperature of the sample and environmental conditions (when necessary).

i) Indication of the accuracy and repeatability.

j) Mode field diameter.

5.1.4 Third alternative test method: Bidirectional backscatter difference

5.1.4.1 General

The mode field diameter is determined from the difference in bidirectional backscatter across a splice with a dead-zone fibre with a known mode field diameter:

$$w_s = w_d 10^{\frac{g(L_d - L_s) + f}{20}} \tag{5-4}$$

where:

- w_d is the mode field diameter of the dead-zone fibre
- w_s is the mode field diameter of the specimen fibre
- L_d is the change in backscatter (dB) across the splice when measuring from the dead-zone fibre
- L_s is the change in backscatter (dB) across the splice when measuring from the specimen fibre
- g is a wavelength and fibre design dependent adjustment factor
- f is a wavelength and fibre design dependent adjustment factor

5.1.4.2 Test apparatus

As in clause 5.4.2.2, with the following additional requirements:

Figure 2 shows a schematic diagram of an apparatus that uses an optical switch. Use of such an apparatus is optional.

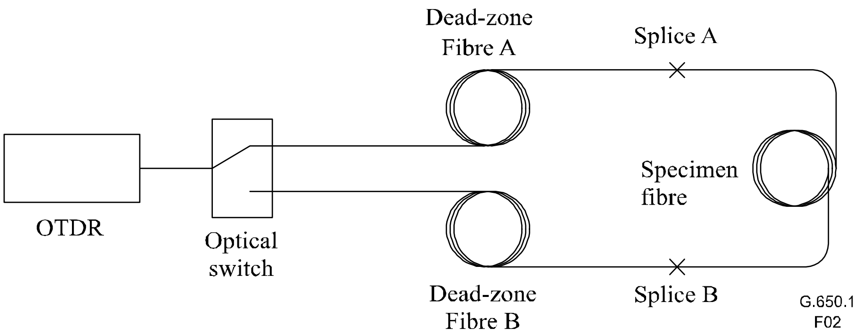


Figure 2 – Optional apparatus for bidirectional backscatter

The optical time domain reflectometer source wavelength shall be known to be within 2 nm. A shift of 2 nm will introduce error of about 0.02 µm for measurements at 1310 nm to 1550 nm.

A dead-zone fibre shall be long enough to prevent the dead-zone region from including the splice or butt-joint with the specimen fibre. The MFD of the dead-zone fibre shall be measured for each wavelength for which measurements are needed with either the RTM or the first or second alternative methods. The dead-zone fibre is typically the same design as the fibre under test.

The splice or butt-joint shall be sufficiently stable over the time the measurement is completed so that the results are not affected. Index matching fluid is recommended when a butt-joint is used in order to minimize reflections.

5.1.4.3 Measurement procedure

This procedure is in two parts: The first is the procedure for a given fibre and wavelength once the adjustment factors, *g* and *f* are known. The second is the procedure for qualifying a given fibre type and design at a given wavelength. The qualification procedure includes the accurate calculation of the adjustment factors, *g* and *f*, that allow correction for OTDR wavelength off nominal. Where *g* and *f* are unknown and accurate determination is impractical, nominal values of 1 and 0, respectively, may be assumed.

5.1.4.3.1 Measurement of a fibre at a given wavelength

a) Align the fibre so that light is launched from the dead-zone fibre A into the specimen fibre. (From the OTDR across splice A into the specimen fibre as shown in Figure 2).

b) Measure the change in backscatter across the splice (splice A as shown in Figure 2), avoiding any reflection, and record the value as L_d.

c) Align the fibre so that light is launched from the specimen fibre into the dead-zone fibre A. (From the OTDR, across splice B into the specimen fibre, then across splice A in Figure 2).

d) Measure the change in backscatter across the splice (splice A as shown in Figure 2), avoiding any reflection, and record the value as L_s.

e) Calculate the mode field diameter according to Equation 5-4.

5.1.4.3.2 Qualification for a fibre type, design, and wavelength

a) Select a sample of fibres of the type and design to be measured, for which the mode field diameter, w_s, has been measured at the desired wavelength using either the reference test method or the first or second alternative methods, such that the range of mode field diameter values for the fibre type and design are represented in the sample.

b) Complete the procedure a) to d) of clause 5.1.4.3.1 to determine the changes in backscatter across the splice L_d and L_s.

c) Compute $20\log_{10}\left(\frac{w_s}{w_d}\right)$ for each fibre and perform a linear regression of it versus $(L_d - L_s)$ to determine g (slope) and f (intercept).

d) Select a second sample of fibres, independent from the first set to determine g and f, for which the mode field diameter has also been measured at the desired wavelength using either the reference test method or the first or second alternative methods.

e) Complete the procedure in clause 5.1.4.3.1, using the values of g and f determined in c) to determine the mode field diameter, w_s. Find the difference to the value measured with the reference test method or the first or second alternative methods.

f) Calculate the average difference (bias), and the standard deviation of differences (σ_d) to determine if equivalence has been demonstrated.

g) An acceptable measure of equivalence may be obtained by calculating the equivalence level, B, where B = |bias| + 2 σ_d/sqrt(n), with n being the sample size. A typical upper limit on B is 0.1 µm.

h) If B exceeds the upper limit, adjustments to the procedure such as improving the splice or butt-joint are recommended.

5.1.4.4 Presentation of results

For each fibre measured:

a) Nominal wavelength.

b) Mode field diameter value.

c) Fibre identification.

Information to be available:

a) Description of the apparatus.

b) Qualification data for each fibre type, design, and wavelength.

c) Indication of accuracy and repeatability.

5.2 Test methods for the cladding diameter, core concentricity error and cladding non-circularity

5.2.1 Reference test method: The near-field image technique

5.2.1.1 General

The glass geometry parameters are determined from the near-field intensity distribution, according to the definitions given in clauses 3.4.3, 3.4.6 and 3.4.8.

5.2.1.2 Test apparatus

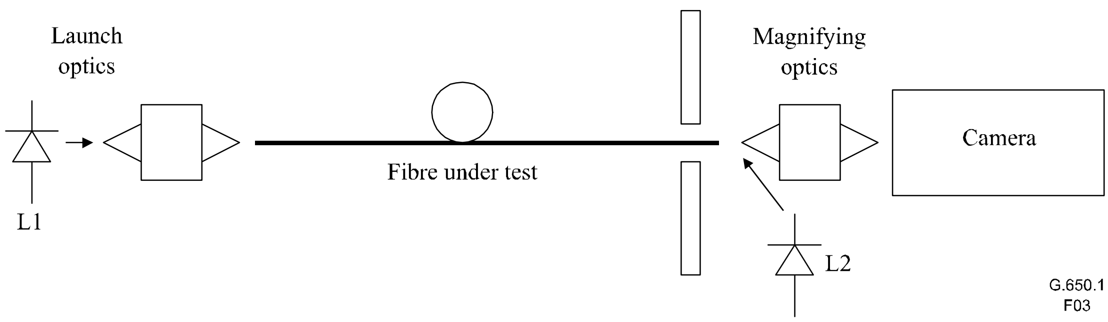


Figure 3 – A scheme for the test apparatus

5.2.1.2.1 Light sources

A light source, L1, for illuminating the core shall be chosen adjustable in intensity and stable in position over a period of time sufficiently long to complete the measurement procedure. Wavelengths above and/or below the fibre's cut-off wavelength may be used. A second light source, L2, with similar characteristics, shall be used to illuminate the cladding.

5.2.1.2.2 Launching conditions

The launch optics shall be arranged so that the light source uniformly overfills the fibre angularly and spatially. At the output end, the cladding shall be illuminated uniformly.

NOTE – The launching conditions from source L1 shall be such as to determine a circularly symmetric spatial field distribution at the output of the fibre.

5.2.1.2.3 Cladding mode stripper

Cladding mode light shall be stripped from the specimen near the input end. When the fibre under test has a primary coating with a refractive index higher than that of the glass, this coating acts as a cladding mode stripper.

5.2.1.2.4 Specimen

The specimen shall be a short length of the optical fibre to be measured. The fibre ends shall be clean, smooth, and perpendicular to the fibre axis.

5.2.1.2.5 Magnifying optics

The magnifying optics shall consist of an optical system (e.g., a microscope objective) which magnifies the specimen output near-field, focusing it onto the plane of the detector. The numerical aperture and hence the resolving power of the optics shall be compatible with the measuring accuracy required, and not lower than 0.3. The magnification shall be selected to be compatible with the desired resolution, and shall be recorded.

5.2.1.2.6 Detector

CCD video cameras, scanning vidicons, or other pattern/intensity recognition devices shall be used to detect the magnified output near-field image and transmit it to a video monitor. The video digitizer performs the digitization of the image for further computer analysis. The video system shall be sufficiently linear such that, after calibration, the measurement uncertainty is not greater than required.

5.2.1.2.7 Video image monitor

A video image monitor shall be used to display the detected image. The screen on the monitor typically shows a pattern, such as cross-hairs, to assist the operator in centring the image of the specimen. Computer-controlled alignment and/or focusing may be used.

5.2.1.2.8 Data system

The measurement, the data acquisitions, and the calculations are performed using a computer. A printer provides a hard copy of the information and measurement results.

5.2.1.3 Measurement procedure

5.2.1.3.1 Calibration

Calibration shall be according to the procedures given in [IEC 61745].

5.2.1.3.2 Measurement

The prepared specimen shall be aligned at the input end to achieve the launch condition specified. The near-field image of the output end shall be focused and centred in the monitor. The intensity of the core image illumination at the input end and the intensity of the cladding image illumination at the output end shall be adjusted according to an established, internal standard for the particular test equipment.

The digitized video image of the output face shall be recorded and the points representing both the cladding image edge and the core image edge shall be determined and recorded in edge tables. The decision levels of the boundaries in the near-field image are the following:

Core image boundary: This level shall be chosen from 5% to 50% of the maximum near-field intensity.

Cladding image boundary: Different methods for determining the cladding boundary can be used, depending on the illumination method. The method used in practice shall be the same as that used in calibration.

5.2.1.3.3 Calculations

The raw data of the core and cladding edge are fitted to smooth, mathematically closed forms to determine best estimates of the actual edges. These smooth mathematically closed forms are then fitted to a circle in order to determine the geometrical characteristics, including the first order deviations from the ideal circular shape of each respective edge boundary. These values and the mathematical edge representation are used to determine the parameters as follows:

– Xco, Yco (μm) fitted core centre;
– Rcl (μm) fitted cladding radius;
– Xcl, Ycl (μm) fitted cladding centre;
– Rmincl (μm) minimum distance of the cladding edge to centre;
– Rmaxcl (μm) maximum distance of the cladding edge to centre;
– Cladding diameter (μm) = 2Rcl;
– Cladding non-circularity (%) = 100(Rmaxcl – Rmincl)/Rcl;
– Core concentricity error (μm) = $[(Xcl - Xco)^2 + (Ycl - Yco)^2]^{1/2}$.

The smooth mathematically closed forms used to represent the edges are required to allow a variation of curvature that is greater than or equal to that found in an ellipse. For non-elliptical forms, the data can be converted to polar coordinates about a roughly estimated centre before fitting the radius vs angular position.

Active filtering, or removal of raw data points that represent cleave damage from those that are fitted to the mathematical form, is allowed. The choice of the curve, the equipment, the cleave method and the filtration algorithm are interactive in their contribution to the quality of the cladding measurement results.

5.2.1.4 Presentation of the results

For each measurement:

a) Fibre identification.
b) The parameters: cladding diameter, cladding non-circularity, and core concentricity error.

Information to be available:

a) Test set-up arrangement.
b) Launching conditions.
c) Spectral characteristics.
d) Magnification factor.
e) Type and dimensions of the detector.

f) Indication of accuracy and repeatability, including calibration data.

5.2.2 First alternative test method: The refracted near-field technique

5.2.2.1 General

The refracted near-field measurement gives directly the refractive index distribution across the entire fibre (core and cladding). The geometrical characteristics of the fibre can be obtained from the refractive index distribution using suitable algorithms.

5.2.2.2 Test apparatus

A schematic diagram of the measurement method is shown in Figure 4. The technique involves scanning of a focused spot of light across the end of the fibre. The launch optics are arranged to overfill the numerical aperture of the fibre. The fibre end is immersed in a fluid of slightly higher index than the cladding. Part of the light is guided down the fibre and the rest appears as a hollow cone outside the fibre. A disc is placed on the axis of the core to ensure that only refracted light reaches the detector.

The optical resolution, and hence the ability to resolve details in the fibre geometry, depends on the size of the focused spot of light. This depends both on the numerical aperture of the focusing lens and on the size of the disc. However, the position of sharp features can be resolved to much better accuracy than this, dependent on step size for stepper motor systems, or position monitoring accuracy of analogue drives.

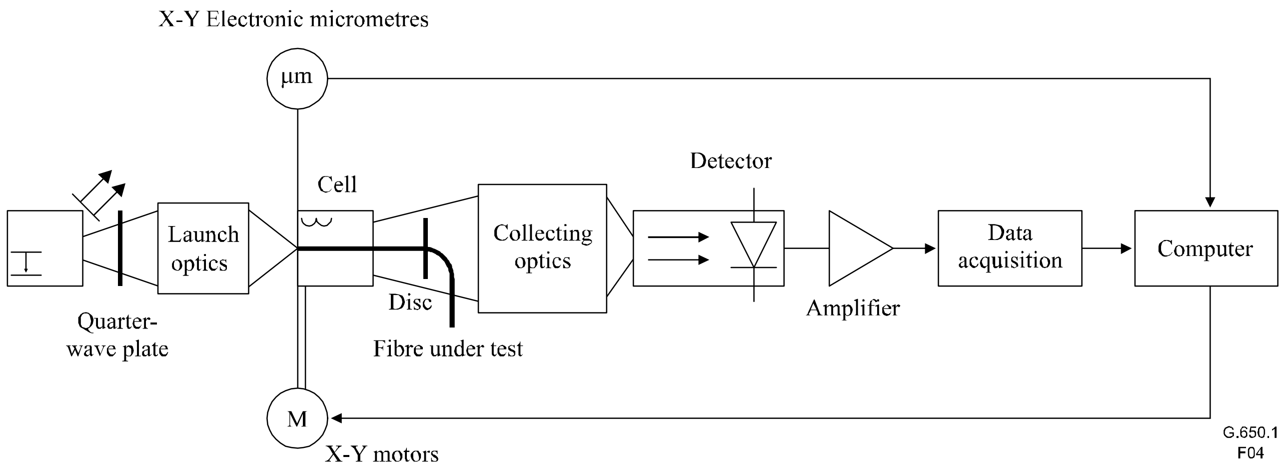


Figure 4 – Typical arrangement of the refracted near-field test set-up

5.2.2.2.1 Source

A stable laser giving about 1 mW of power in the TEM_{00} mode is required, such as a HeNe laser.

A quarter-wave plate is introduced to change the beam from linear to circular polarization because the reflectivity of light at an air-glass interface is strongly angle- and polarization-dependent.

5.2.2.2.2 Launching conditions

The launch optics, which are arranged to overfill the numerical aperture of the fibre, bring a beam of light to a focus on the flat end of the fibre. The optical axis of the beam of light should be within 1° of the axis of the fibre. The resolution of the equipment is determined by the size of the focused spot, which should be as small as possible in order to maximize the resolution, e.g., less than 1.0 µm. The equipment enables the focused spot to be scanned across the fibre cross-section.

5.2.2.2.3 Cell

The cell will contain a fluid with a refractive index slightly higher than that of the fibre cladding. The position of the cell will be controlled by X-Y motors driven by the computer and detected by X-Y micrometres.

5.2.2.2.4 Detection

The refracted light is collected by suitable collecting optics and brought to the detector in any convenient manner provided that all the refracted light is collected. By calculation, the required size of disc and its position along the central axis can be determined.

5.2.2.2.5 Data acquisition

The measured intensity distribution can be recorded, processed and presented in a suitable form, according to the scanning technique and to the specification requirements. A computer will be used to drive the X-Y motors, to record the X-Y position of the cell and the corresponding power levels, and to process the measured data.

5.2.2.3 Procedure

Refer to the schematic diagram of the test apparatus (Figure 4).

5.2.2.3.1 Preparation of fibre under test

A length of fibre less than 2 m is required.

Primary fibre coating shall be removed from the section of fibre immersed in the fluid cell.

The fibre ends shall be clean, smooth and perpendicular to the fibre axis.

5.2.2.3.2 Equipment calibration

The equipment is calibrated with the fibre removed from the fluid cell. During the measurement, the angle of the cone of light varies according to the refractive index seen at the entry point to the fibre (hence the change of power passing the disc). With the fibre removed and the fluid index and cell thickness known, this change in angle can be simulated by translating the disc along the optic axis. By moving the disc to a number of predetermined positions, one can scale the profile in terms of relative index. Absolute index can only be found if the cladding or fluid index is known accurately at the measurement wavelength and temperature.

More convenient calibration procedures can be performed by means of a thin rod of known constant refractive index or by means of a multimode-multistep fibre, where the various refractive index values are known with great accuracy. This latter technique can also be useful in checking the linearity of the apparatus. Under this respect, it may also be useful to control the fluid temperature in the fluid cell.

5.2.2.3.3 Raster scan

The launch end of the fibre to be measured is immersed in the fluid cell and the laser beam is simultaneously centred and focused on the fibre end face.

The disc is centred on the output cone. Refracted modes passing the disc are collected and focused onto the detector.

The focused laser spot is scanned across the fibre end cross-section and a two-dimensional distribution of fibre refractive index is directly obtained. From this distribution, the geometrical characteristics will be calculated.

5.2.2.3.4 Geometrical characteristics

Once the raster scan of refractive index is performed, the core contour is obtained taking the points at the core-cladding interface of refractive index coinciding with the mean value between the averaged refractive indices of core and cladding respectively. The cladding contour is determined in a similar way but at the cladding-index matching fluid interface. Geometry analyses consistent with the terms in clause 3 will be performed starting from the core and cladding contours data. An index profile measurement actually yields the core concentricity error.

5.2.2.4 Presentation of the results

a) Test set-up arrangement and indication of the scanning technique used.

b) Fibre identification.

c) Cladding diameter.

d) Core concentricity error.

e) Cladding non-circularity.

f) Core diameter (if required).

g) Raster scan across the entire fibre (if required).

h) Indication of accuracy and repeatability.

i) Temperature of the sample and environmental conditions (if necessary).

5.2.3 Second alternative test method: The side-view technique

5.2.3.1 General

The side-view method is applied to single-mode fibres to determine geometrical parameters (core concentricity error, cladding diameter and cladding non-circularity) by measuring the intensity distribution of light that is refracted inside the fibre.

5.2.3.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure 5.

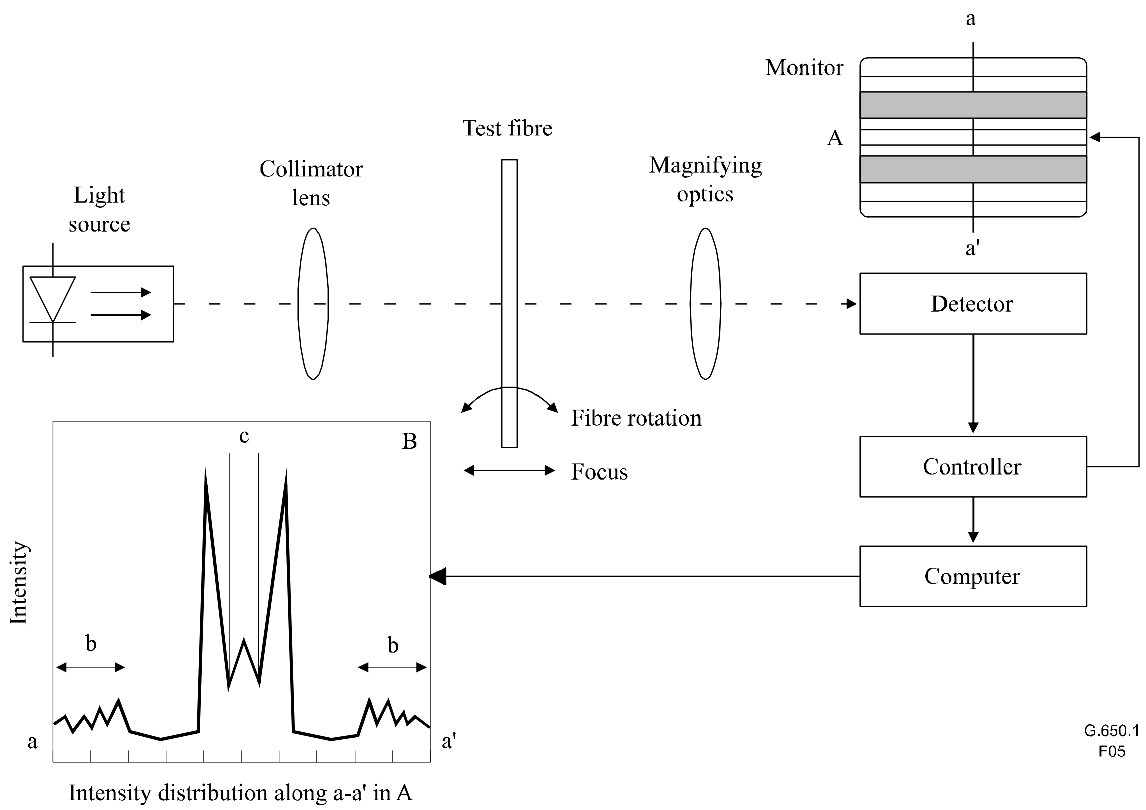


Figure 5 – Schematic diagram of side-view measurement system

5.2.3.2.1 Light source

The emitted light shall be collimated, adjustable in intensity and stable in position, intensity and wavelength over a time period sufficiently long to complete the measuring procedure. A stable and high intensity light source such as a light emitting diode (LED) may be used.

5.2.3.2.2 Specimen

The specimen to be measured shall be a short length of single-mode fibre. The primary fibre coating shall be removed from the observed section of the fibre. The surface of the fibre shall be kept clean during the measurement.

5.2.3.2.3 Magnifying optics

The magnifying optics shall consist of an optical system (e.g., a microscope objective) which magnifies the intensity distribution of refracted light inside the fibre onto the plane of the scanning detector. The observation plane shall be set at a fixed distance forward from the fibre axis. The magnification shall be selected to be compatible with the desired spatial resolution and shall be recorded.

5.2.3.2.4 Detector

A suitable detector shall be employed to determine the magnified intensity distribution in the observation plane along the line perpendicular to the fibre axis. A vidicon or charge coupled device can be used. The detector must have linear characteristics in the required measuring range. The detector's resolution shall be compatible with the desired spatial resolution.

5.2.3.2.5 Data processing

A computer with appropriate software shall be used for the analysis of the intensity distributions.

5.2.3.3 Measurement procedure

5.2.3.3.1 Equipment calibration

For equipment calibration, the magnification of the magnifying optics shall be measured by scanning the length of a specimen whose dimensions are already known with suitable accuracy. This magnification shall be recorded.

5.2.3.3.2 Measurement

The test fibre is fixed in the sample holder and set in the measuring system. The fibre is adjusted so that its axis is perpendicular to the optical axis of the measuring system.

Intensity distributions in the observation plane along the line perpendicular to the fibre axis (a-a' in A, in Figure 5) are recorded (shown as B) for different viewing directions, by rotating the fibre around its axis, keeping the distance between the fibre axis and the observation plane constant. Cladding diameter and the central position of the fibre are determined by analysing the symmetry of the radial intensity distribution in the magnified image (shown as b in B). The central position of the core is determined by analysing the intensity distribution of converged light (shown as c). The distance between the central position of the fibre and that of the core corresponds to the nominal observed value of core concentricity error.

As shown in Figure 6, fitting the sinusoidal function to the experimentally obtained values of the mode field concentricity error (see Note 2 in clause 3.4.7) plotted as a function of the rotation angle, the actual core concentricity error is calculated as the product of the maximum amplitude of the sinusoidal function and magnification factor with respect to the lens effect due to the cylindrical-structure of the fibre. The cladding diameter is evaluated as an averaged value of measured fibre diameters at each rotation angle, resulting in values for maximum and minimum diameters to determine the value of cladding non-circularity according to the definition.

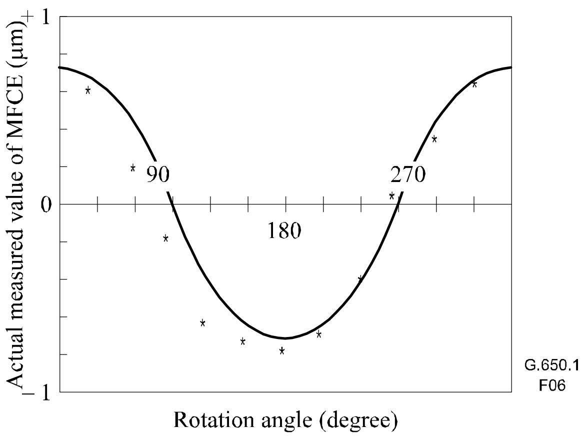


Figure 6 – Measured value of the mode field concentricity error as a function of rotation angle

5.2.3.4 Presentation of the results

a) Test arrangement.

b) Fibre identification.

c) Spectral characteristics of the source.

d) Indication of repeatability and accuracy.

e) Plot of nominal core concentricity error versus rotation angle.

f) Core concentricity error, cladding diameter and cladding non-circularity.

g) Temperature of the sample and environmental conditions (if necessary).

5.2.4 Third alternative test method: The transmitted near-field technique

5.2.4.1 General

The geometrical parameters are determined from the near-field intensity distribution according to the definitions given in clauses 3.4.3, 3.4.6 and 3.4.8.

Since mode field concentricity is a good approximation of core concentricity, this method can be used to evaluate core concentricity error.

5.2.4.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure 7.

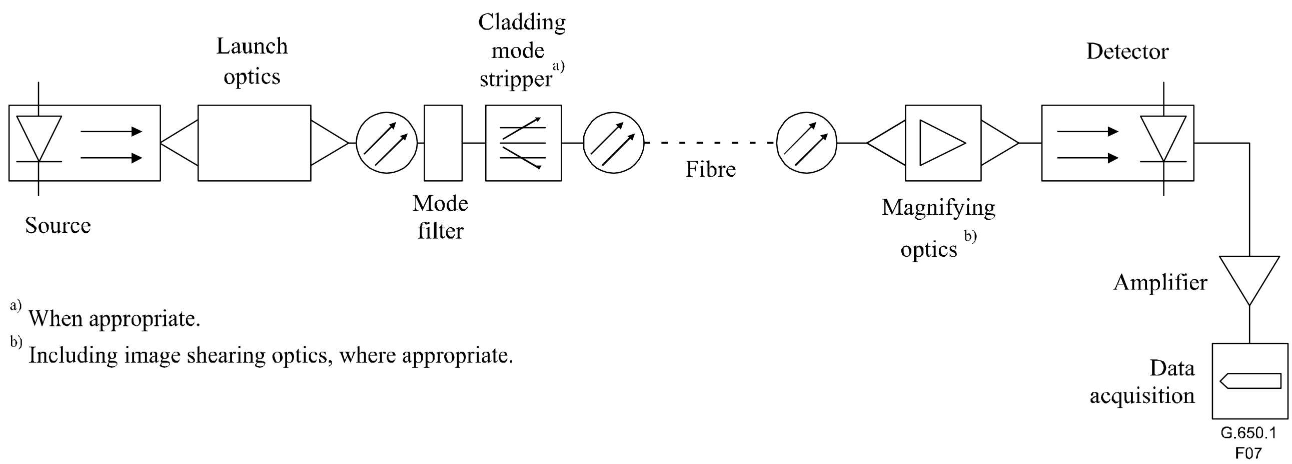


Figure 7 – Typical arrangement of the transmitted near-field set-up

5.2.4.2.1 Light source

A nominal 1310 nm (for fibres covered by [ITU-T G.652]) or 1550 nm (for fibres covered by [ITU-T G.653] and [ITU-T G.654]) light source for illuminating the core shall be used. The light source shall be adjustable in intensity and stable in position, intensity and wavelength over a time period sufficiently long to complete the measurement procedure. The spectral characteristics of this source should be chosen to preclude multimode operation. A second light source with similar characteristics can be used, if necessary, for illuminating the cladding. The spectral characteristics of the second light source must not cause defocusing of the image.

5.2.4.2.2 Launching conditions

The launch optics, which will be arranged to overfill the fibre, will bring a beam of light to a focus on the flat input end of the fibre.

5.2.4.2.3 Mode filter

In the measurement, it is necessary to assure single-mode operation at the measurement wavelength. In these cases, it may be necessary to introduce a bend in order to remove the LP_{11} mode.

5.2.4.2.4 Cladding mode stripper

A suitable cladding mode stripper shall be used to remove the optical power propagating in the cladding. When measuring the geometrical characteristics of the cladding only, the cladding mode stripper shall not be present.

5.2.4.2.5 Specimen

The specimen shall be a short length of the optical fibre to be measured. The fibre ends shall be clean, smooth and perpendicular to the fibre axis.

5.2.4.2.6 Magnifying optics

The magnifying optics shall consist of an optical system (e.g., a microscope objective) which magnifies the specimen output near-field, focusing it onto the plane of the scanning detector. The numerical aperture, and hence the resolving power of the optics, shall be compatible with the measuring accuracy required, and not lower than 0.3. The magnification shall be selected to be compatible with the desired spatial resolution, and shall be recorded.

5.2.4.2.7 Detector

A suitable detector shall be employed which provides the point-to-point intensity of the transmitted near-field pattern(s). For example, any of the following techniques can be used:

a) scanning photodetector with pinhole aperture;

b) scanning mirror with fixed pinhole aperture and photodetector;

c) scanning vidicon, charge coupled devices or other pattern/intensity recognition devices.

The detector shall be linear (or shall be linearized) in behaviour over the range of intensities encountered.

5.2.4.2.8 Amplifier

An amplifier may be employed in order to increase the signal level. The bandwidth of the amplifier shall be chosen according to the type of scanning used. When scanning the output end of the fibre with mechanical or optical systems, it is customary to modulate the optical source. If such a procedure is adopted, the amplifier should be linked to the source modulation frequency.

5.2.4.2.9 Data acquisition

The measured intensity distribution can be recorded, processed and presented in a suitable form, according to the scanning technique and to the specification requirements.

5.2.4.3 Measurement procedure

5.2.4.3.1 Equipment calibration

For the equipment calibration, the magnification of the magnifying optics shall be measured by scanning the image of a specimen whose dimensions are already known with suitable accuracy.

This magnification shall be recorded.

5.2.4.3.2 Measurement

The launch end of the fibre shall be aligned with the launch beam, and the output end of the fibre shall be aligned to the optical axis of the magnifying optics. For transmitted near-field measurement, the focused image(s) of the output end of the fibre shall be scanned by the detector, according to the specification requirements. The focusing shall be performed with maximum accuracy, in order to reduce dimensional errors due to the scanning of a defocused image. The desired geometrical parameters are then calculated according to the definitions.

Algorithms for defining edges and calculating the geometrical parameters are under study.

5.2.4.4 Presentation of the results

a) Test set-up arrangement, with indication of the scanning technique used.

b) Launching conditions.

c) Spectral characteristics of the source(s).

d) Fibre identification and length.

e) Type of mode filter (if applicable).

f) Magnification of the magnifying optics.

g) Type and dimensions of the scanning detector.

h) Temperature of the sample and environmental conditions (when necessary).

i) Indication of the accuracy and repeatability.

j) Resulting dimensional parameters, such as cladding diameters, cladding non-circularities, core concentricity error, etc.

5.3 Test methods for the cut-off wavelength

5.3.1 Reference test method for the cut-off wavelength (λ_c) of the primary coated fibre: The transmitted power technique

5.3.1.1 General

The cut-off wavelength measurement of single-mode fibres is intended to assure effective single-mode operation above a specified wavelength.

The transmitted power technique uses the variation with wavelength of the transmitted power of a short length of the fibre under test, under defined conditions, compared to a reference transmitted power. There are two possible ways to obtain this reference power:

a) the test fibre with a loop of smaller radius; or

b) a short (1-2 m) length of multimode fibre.

NOTE – The presence of a primary coating on the fibre usually does not affect the cut-off wavelength. However, the presence of a secondary coating may result in a cut-off wavelength that may be significantly shorter than that of the primary coated fibre.

The measurement may be performed on a fibre having a secondary coating if the secondary coating type has been examined and it has been confirmed that it does not significantly affect the cut-off wavelength, provided that the secondary coating is properly applied.

5.3.1.2 Test apparatus

5.3.1.2.1 Light source

A light source with linewidth not exceeding 10 nm (FWHM), stable in position, intensity and wavelength over a time period sufficient to complete the measurement procedure, and capable of operating over a sufficient wavelength range, shall be used.

5.3.1.2.2 Modulation

It is customary to modulate the light source in order to improve the signal/noise ratio at the receiver. If such a procedure is adopted, the detector should be linked to a signal processing system synchronous with the source modulation frequency. The detecting system should be substantially linear.

5.3.1.2.3 Launching conditions

The launching conditions must be used in such a way as to excite substantially uniformly both LP_{01} and LP_{11} modes. For example, suitable launching techniques could be:

a) jointing with a multimode fibre; or

b) launching with a suitable large spot-large NA optics.

5.3.1.2.4 Cladding mode stripper

The cladding mode stripper is a device that encourages the conversion of cladding modes to radiation modes; as a result, cladding modes are stripped from the fibre. Care should be taken to avoid affecting the propagation of the LP_{11} mode.

5.3.1.2.5 Optical detector

A suitable detector shall be used so that all of the radiation emerging from the fibre is intercepted. The spectral response should be compatible with the spectral characteristics of the source. The detector must be uniform and have linear sensitivity.

5.3.1.3 Measurement procedure

5.3.1.3.1 Standard test sample

The measurement shall be performed on a 2 m length of fibre. The fibre is inserted into the test apparatus and bent to form a loosely constrained loop. The loop shall complete one full turn of a circle of 140 mm radius. The remaining part of the fibre shall be substantially free of external stresses. While some incidental bends of larger radii are permissible, they must not introduce a significant change in the measurement result. The output power $P_1(\lambda)$ shall be recorded versus λ in a sufficiently wide range around the expected cut-off wavelength.

5.3.1.3.2 Transmission through the reference sample

Either method a) or b) may be used.

a) Using the test sample, and keeping the launch conditions fixed, an output power $P_2(\lambda)$ is measured over the same wavelength range with at least one loop of sufficiently small radius in the test sample to filter the LP_{11} mode. The exact value of the smaller radius may be determined prior to measurement. It should be small enough to attenuate the second-order mode but not the primary mode, but not too small in order to avoid macrobending effects at higher wavelengths. A radius between 10 and 30 mm is typical for most ITU-T G.652 to ITU-T G.656 fibres. For some ITU-T G.657 fibres, the radius must be much smaller.

b) With a short (1-2 m) length of multimode fibre, an output power $P_3(\lambda)$ is measured over the same wavelength range.

NOTE 1 – The presence of leaky modes may cause ripple in the transmission spectrum of the multimode reference fibre, affecting the result. To reduce this problem, light-launching conditions may be restricted to fill only 70% of the multimode fibre's core diameter and NA or a suitable mode filter may be used.

NOTE 2 – For some ITU-T G.657 fibres, because of the bending-loss insensitive nature of these fibres, method a) may not be adequate, it is recommended to use method b) as a reference scan for these fibres.

5.3.1.3.3 Calculations

The spectral attenuation of the test specimen, relative to the reference power is:

$$a(\lambda) = 10\log\frac{P_1(\lambda)}{P_i(\lambda)} \tag{5-5}$$

where i = 2 or 3 for methods a) or b), respectively, in clause 5.3.1.3.2.

Assuming a straight-line representation of the upper wavelength region, the deviation of higher-order modes from the fundamental mode is:

$$\Delta a(\lambda) = a(\lambda) - (A_u + B_u\lambda) \tag{5-6}$$

A_u and B_u are determined so that $(A_u + B_u\lambda)$ represents the portion of the spectral attenuation curve at wavelengths above the region where the attenuation of higher order modes is accelerated (transition region). For method a), both A_u and B_u may be set to zero. See Figures 8a and 9a.

NOTE – In method a) in clause 5.3.1.3.2, the small mode filter fibre loop eliminates all modes except the fundamental for wavelengths greater than a few tens of nm below the cut-off wavelength λ_c. For wavelengths more than several hundred nm above λ_c, even the fundamental mode may be strongly attenuated by the loop. a(λ) is equal to the logarithmic ratio between the total power emerging from the sample, including the LP_{11} mode power, and the fundamental mode power. When the modes are uniformly excited in accordance with clause 5.3.1.2.3, a(λ) then also yields the LP_{11} mode attenuation A(λ) in dB in the test sample:

$$A(\lambda) = 10\log\left[\left(\frac{P_1(\lambda)}{P_2(\lambda)} - 1\right)/2\right] \tag{5-7}$$

5.3.1.3.4 Determination of cut-off wavelength

In the transition region, higher-order mode power is reduced with increasing wavelength. Fibre cut-off wavelength, λ_c, is defined as the wavelength at which the higher-order mode power relative to the fundamental mode power, Δa(λ), has been reduced to 0.1 dB.

Figures 8b and 9b illustrate "humps" that sometimes appear near the cut-off wavelength. In the absence of humps (see Figures 8a and 9a), accurate determination of λ_c can be achieved without algorithms. Optionally, for precision improvement, fitting algorithms based on the following equations can be used when humps are present. Appendix I contains examples of such algorithms.

$$\gamma(\lambda) = 10\log\left[-\frac{10}{A}\log\left(\frac{10^{\Delta a(\lambda)/10} - 1}{\rho}\right)\right] \tag{5-8}$$

$$A = 10\log\left[\rho/\left(10^{0.01} - 1\right)\right] \tag{5-9}$$

Unless otherwise specified, ρ = 2. (5-10)

When the coefficients of:

$$A_t + B_t\lambda = -Y(\lambda) \quad (5\text{-}11)$$

are determined for wavelengths in the transition region, then:

$$\lambda_c = -\frac{A_t}{B_t} \quad (5\text{-}12)$$

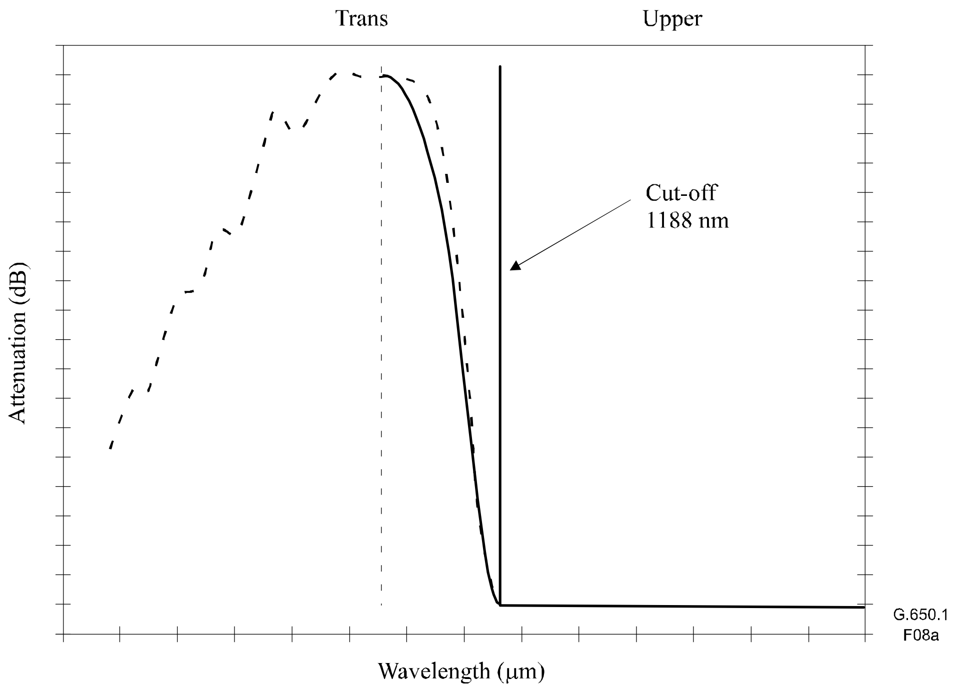


Figure 8a – Single-mode reference cut-off plot

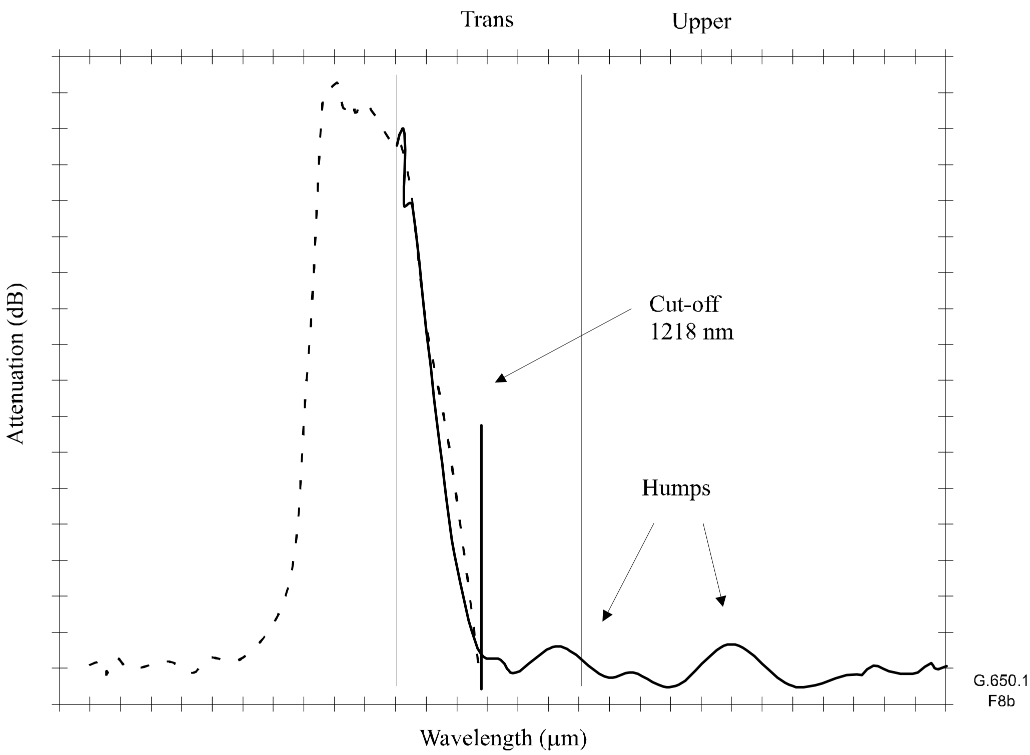


Figure 8b – Single-mode reference cut-off plot with humps

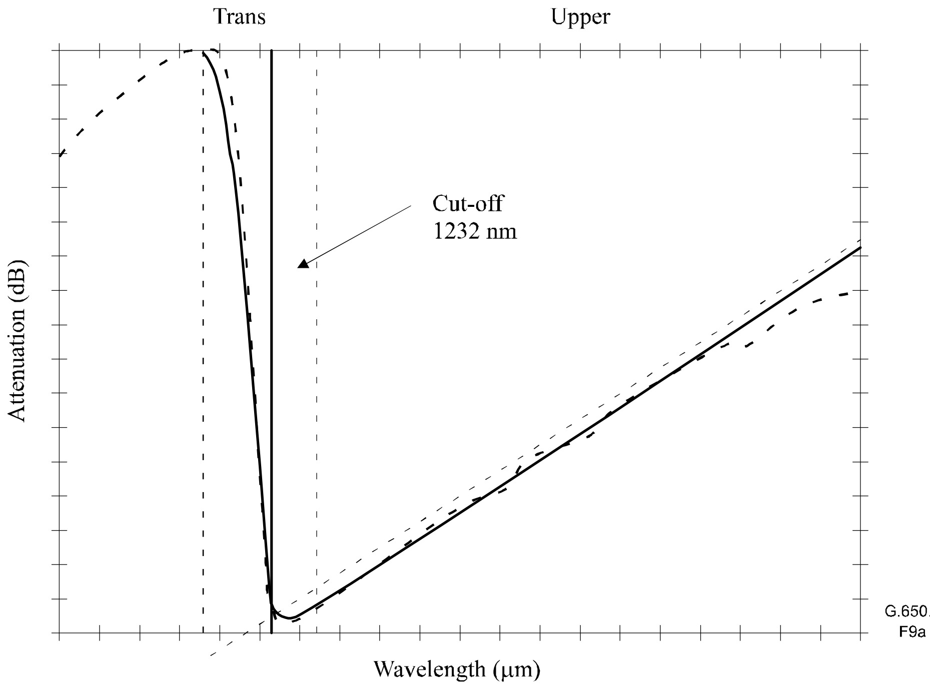


Figure 9a – Multimode reference cut-off plot

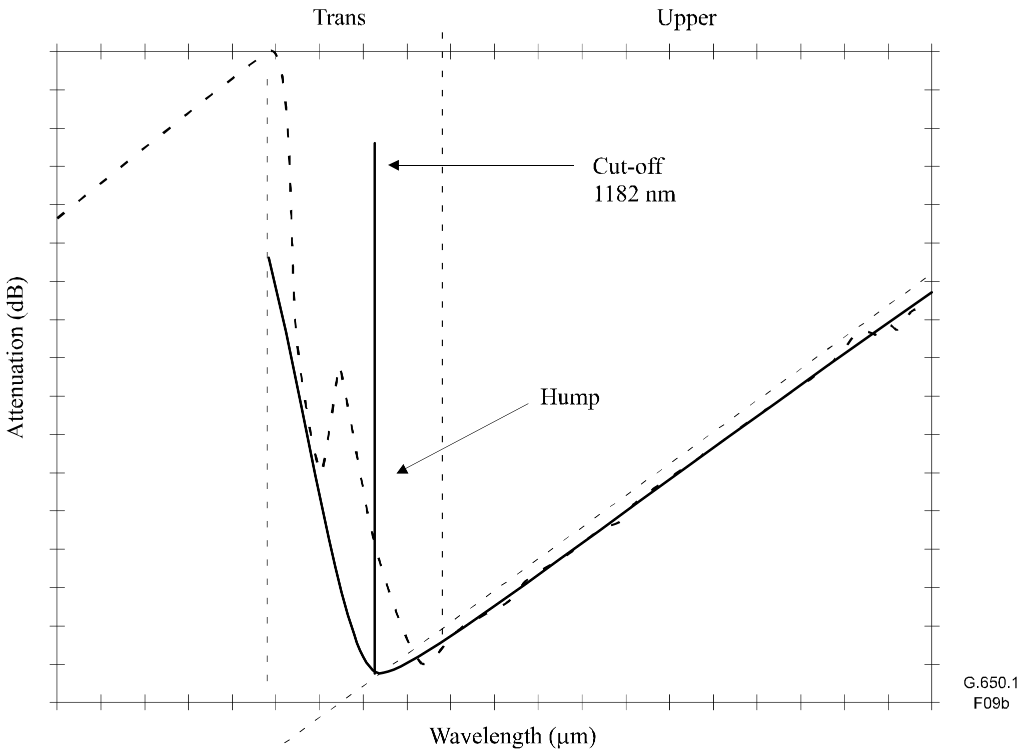


Figure 9b – Multimode reference cut-off plot with hump

NOTE – According to the definition, the LP_{11} mode attenuation in the test sample is 19.3 dB at the cut-off wavelength.

5.3.1.4 Presentation of the results

a) Test set-up arrangement.

b) Launching condition.

c) Type of reference sample.

d) Temperature of the sample and environmental conditions (if necessary).

e) Fibre identification.

f) Wavelength range of measurement.

g) Fibre cut-off wavelength.

h) Plot of a(λ) (if required).

i) Interpolation method (if used).

5.3.2 Alternative test method for λ_c: The split-mandrel technique

5.3.2.1 General (as in clause 5.3.1.1)

5.3.2.2 Test apparatus

5.3.2.2.1 Light source (as in clause 5.3.1.2.1)

5.3.2.2.2 Modulation (as in clause 5.3.1.2.2)

5.3.2.2.3 Launching conditions (as in clause 5.3.1.2.3)

5.3.2.2.4 Cladding mode stripper (as in clause 5.3.1.2.4)

5.3.2.2.5 Optical detector (as in clause 5.3.1.2.5)

5.3.2.3 Measurement procedure

5.3.2.3.1 Standard test sample

The measurement shall be performed on a 2 m length of fibre. The fibre is inserted into the test apparatus and bent to form a loosely constrained loop. The loop shall contain a full turn (360 degrees) consisting of two arcs (180 degrees each) of 140 mm radius, connected by tangents. The remaining part of the fibre shall be substantially free of external stresses. While some incidental bends of larger radii are permissible, they must not introduce a significant change in the measurement result. The output power $P_1(\lambda)$ shall be recorded versus λ in a sufficiently wide range around the expected cut-off wavelength.

As shown in Figure 10, the lower semicircular mandrel moves to take any slack from the fibre loop without requiring movement of the launch or receive optics or placing the fibre sample under any significant tension.

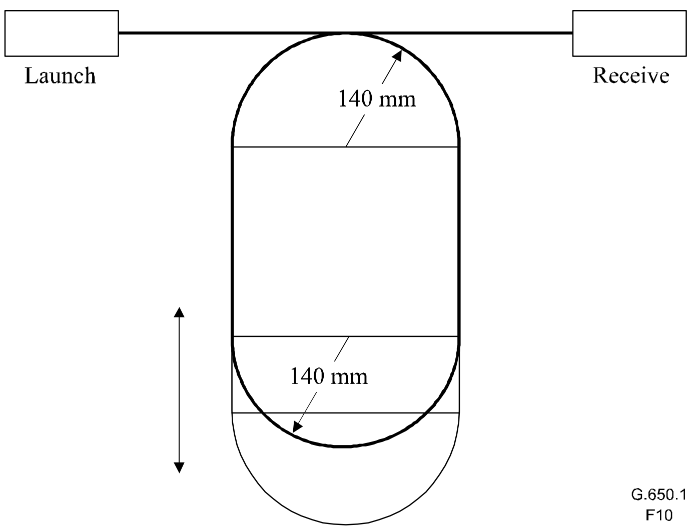


Figure 10 – Fibre deployment: Cut-off wavelength by the split-mandrel technique

5.3.2.3.2 Transmission through the reference sample (as in clause 5.3.1.3.2)

5.3.2.3.3 Calculations (as in clause 5.3.1.3.3)

5.3.2.3.4 Determination of cut-off wavelength (as in clause 5.3.1.3.4**)**

5.3.2.4 Presentation of the results (as in clause 5.3.1.4)

5.3.3 Reference test method for the cut-off wavelength (λ_{cc}) of the cabled fibre: The transmitted power technique

5.3.3.1 General

This cut-off wavelength measurement, which is performed on cabled single-mode fibres in a deployment condition which simulates outside plant minimum cable lengths, is intended to assure effective single-mode operation above a specified wavelength.

The transmitted power technique uses the variation with wavelength of the transmitted power of the fibre cable under test, under defined conditions, compared to a reference transmitted power. There are two possible ways to obtain this reference power:

a) the cabled test fibre with a loop of smaller radius;

b) a short (1-2 m) length of multimode fibre.

5.3.3.2 Test apparatus

5.3.3.2.1 Light source (as in clause 5.3.1.2.1)

5.3.3.2.2 Modulation (as in clause 5.3.1.2.2)

5.3.3.2.3 Launching conditions (as in clause 5.3.1.2.3)

5.3.3.2.4 Cladding mode stripper (as in clause 5.3.1.2.4)

5.3.3.2.5 Optical detector (as in clause 5.3.1.2.5)

5.3.3.3 Measurement procedure

5.3.3.3.1 Standard test sample

The measurement shall be performed on a length of single-mode fibre in a cable. A cable length of 22 m shall be prepared by exposing 1 m uncabled fibre length at each end, and the resulting 20 m cabled portion shall be laid without any small bends which could affect the measurement value. To simulate the effects of a splice organizer, one loop of X = 40 mm radius shall be applied to each uncabled fibre length (see Figure 11). The uncabled fibre is deployed with secondary coating (if present) intact. While some incidental bends of larger radii are permissible in the fibre or cable, they must not introduce a significant change in the measurements. The output power $P_1(\lambda)$ shall be recorded versus λ in a sufficiently wide range around the expected cut-off wavelength.

NOTE 1 – The loops are intended to simulate deployment conditions.

NOTE 2 – Two loops of X = 40 mm radius at one end can be substituted for one loop at each end.

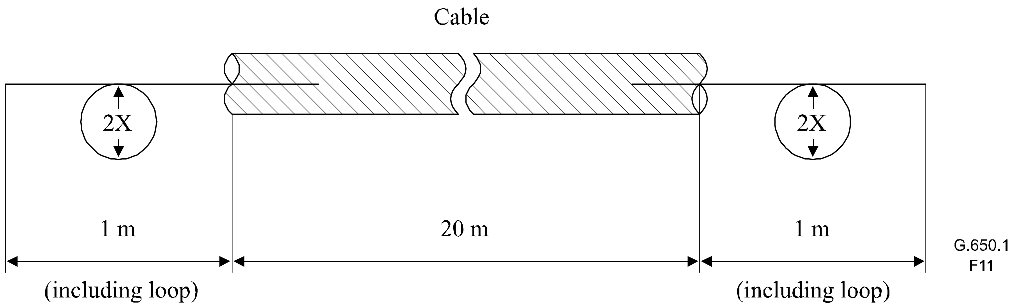


Figure 11 – Deployment condition for measurement of the cabled fibre cut-off wavelength

5.3.3.3.2 Transmission through the reference sample (as in clause 5.3.1.3.2)

5.3.3.3.3 Calculations

The logarithmic ratio between the transmitted powers $P_1(\lambda)$ and $P_i(\lambda)$ is calculated as:

$$R(\lambda) = 10 \log \frac{P_1(\lambda)}{P_i(\lambda)} \tag{5-13}$$

where i = 2 or 3 for methods a) or b) in clause 5.3.1.3.2, respectively.

5.3.3.3.4 Determination of cabled fibre cut-off wavelength

The calculations and method of determining cable cut-off wavelength, λ_{cc}, are the same as for fibre cut-off wavelength. See clauses 5.3.1.3.3 and 5.3.1.3.4.

5.3.3.4 Presentation of the results

a) Test set-up arrangement.

b) Launching condition.

c) Type of reference sample.

d) Temperature of the sample and environmental conditions (if necessary).

e) Fibre and cable identification.

f) Wavelength range of measurement.

g) Cabled fibre cut-off wavelength.

h) Plot of $R(\lambda)$ (if required).

5.3.4 Alternative test method for the cut-off wavelength (λ_{cc}) of the cabled fibre

5.3.4.1 General

The cut-off wavelength measurement is performed on uncabled single-mode fibres in a deployment condition which assures that the results for λ_{cc} are in agreement with those achieved in measurements conducted on cabled fibres.

This method uses the variation in wavelength of the transmitted power of a short length of the fibre under test, under defined conditions, compared to a reference transmitted power. There are two possible ways to obtain this reference power:

a) the test fibre with a loop of a smaller radius; or

b) a short length (1-2 m) of multimode fibre.

5.3.4.2 Test apparatus

5.3.4.2.1 Light source (as in clause 5.3.1.2.1)

5.3.4.2.2 Modulation (as in clause 5.3.1.2.2)

5.3.4.2.3 Launching conditions (as in clause 5.3.1.2.3)

5.3.4.2.4 Cladding mode stripper (as in clause 5.3.1.2.4)

5.3.4.2.5 Optical detector (as in clause 5.3.1.2.5)

5.3.4.3 Measurement procedure

5.3.4.3.1 Standard test sample

The measurement shall be performed on a length of uncabled single-mode fibre. The uncabled fibre is deployed with secondary coating (if present) intact. A fibre length of 22 m is inserted into the test apparatus; the inner 20 m are bent to form loosely constrained loops of a radius r ≥ 140 mm.

One loop of X = 40 mm radius shall be applied to each fibre end (see Figure 12). The output power $P_1(\lambda)$ shall be recorded versus λ in a sufficiently wide range around the expected cut-off wavelength λ_{cc}.

NOTE 1 – The loops are intended to simulate deployment conditions.

NOTE 2 – Two loops of X = 40 mm radius at one end can be substituted for one loop at each end.

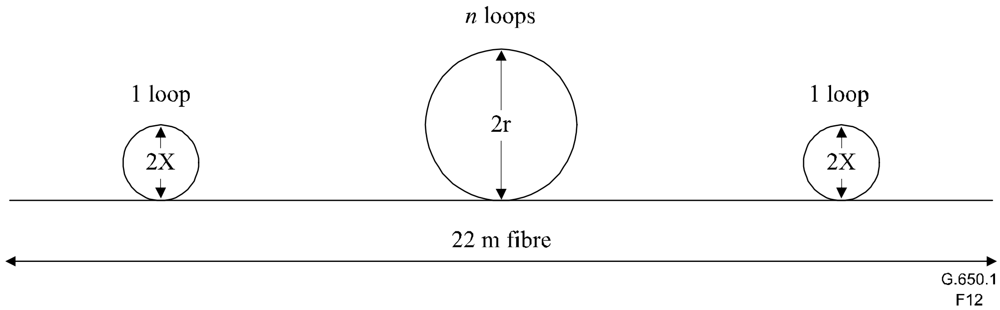


Figure 12 – Deployment condition for measurement of λ_{cc} on uncabled fibres

5.3.4.3.2 Transmission through the reference sample (as in clause 5.3.1.3.2)

5.3.4.3.3 Calculations (as in clause 5.3.1.3.3)

5.3.4.3.4 Determination of cabled fibre cut-off wavelength (as in clause 5.3.3.3.4)

5.3.4.4 Presentation of the results

As in clause 5.3.3.4, and in addition:

– Value of r.

5.4 Test methods for the attenuation

The attenuation tests are intended to provide a means whereby a certain attenuation value may be assigned to a fibre length such that individual attenuation values may be added together to determine the total attenuation of a concatenated length.

NOTE – Attenuation values specified for factory lengths should be measured at room temperature (i.e., a single value in the range 10°C to 35°C).

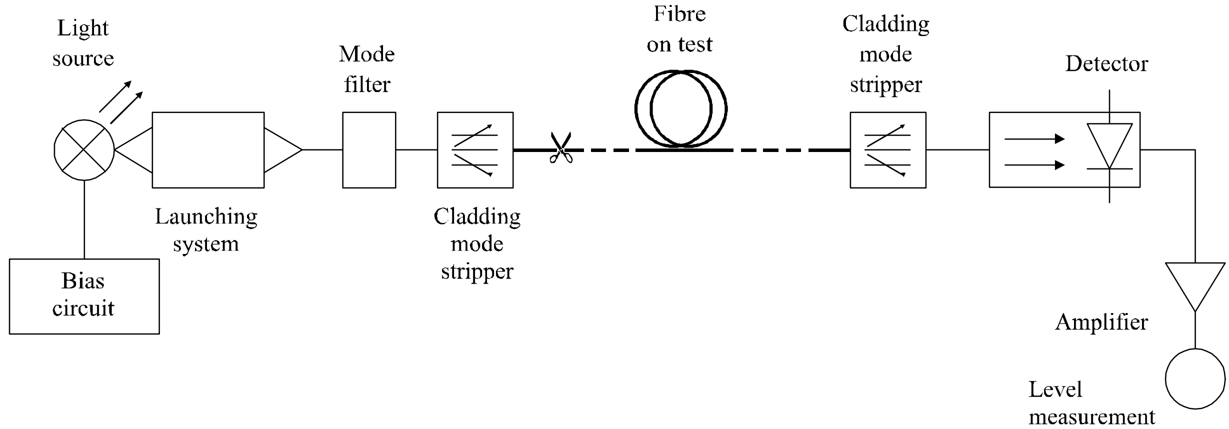
5.4.1 Reference test method: The cut-back technique

5.4.1.1 General

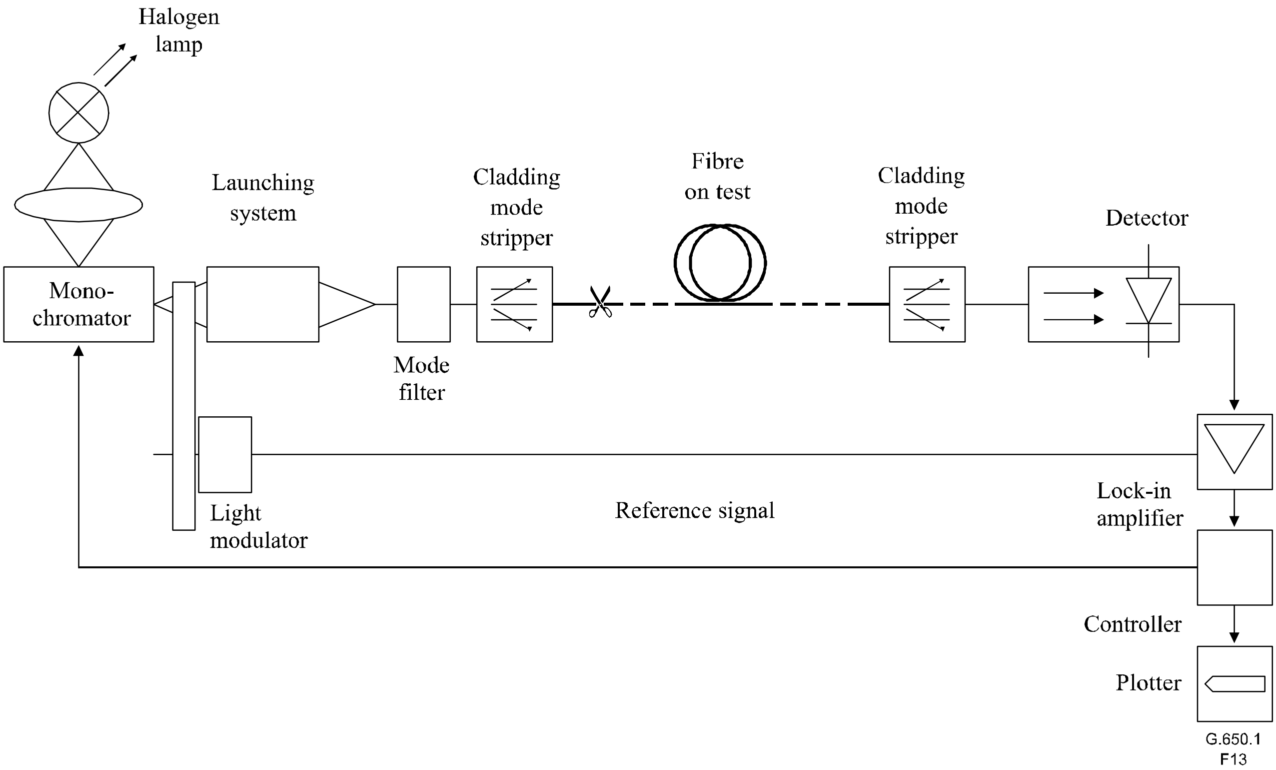
The cut-back technique is a direct application of the definition in which the power levels P_1 and P_2 are measured at two points of the fibre without change of input conditions. P_2 is the power emerging from the far end of the fibre, and P_1 is the power emerging from a point near the input after cutting the fibre.

5.4.1.2 Test apparatus

Measurements may be made at one or more spot wavelengths, or alternatively, a spectral response may be required over a range of wavelengths. Diagrams of suitable test equipments, to obtain one loss or the loss spectrum measurements respectively, are shown as examples in Figure 13.



a) Arrangement of test equipment to make one loss measurement



b) Arrangement of test equipment used to obtain the loss spectrum measurement

Figure 13 – The cut-back technique

5.4.1.2.1 Optical source

A suitable radiation source shall be used as a lamp, laser or light emitting diode. The choice of source depends upon the type of measurement. The source must be stable in position, intensity and wavelength over a time period sufficiently long to complete the measurement procedure. The spectral linewidth (FWHM) shall be specified such that the linewidth is narrow compared with any features of the fibre spectral attenuation.

5.4.1.2.2 Modulation

It is customary to modulate the light source in order to improve the signal/noise ratio at the receiver. If such a procedure is adopted, the detector should be linked to a signal processing system synchronous with the source modulation frequency. The detecting system should be substantially linear in sensitivity.

5.4.1.2.3 Launching conditions

The launching conditions used must be sufficient to excite the fundamental mode. For example, suitable launching techniques could be:

a) jointing with a fibre;

b) launching with a suitable system of optics.

5.4.1.2.4 Mode filter

Care must be taken that higher order modes do not propagate through the cut-back length. In these cases, it may be necessary to introduce a bend in order to remove the higher modes.

5.4.1.2.5 Cladding mode stripper

A cladding mode stripper encourages the conversion of cladding modes to radiation modes; as a result, cladding modes are stripped from the fibre.

5.4.1.2.6 Optical detector

A suitable detector shall be used so that all of the radiation emerging from the fibre is intercepted. The spectral response should be compatible with spectral characteristics of the source. The detector must be uniform and have linear sensitivity characteristics.

5.4.1.3 Measurement procedure

5.4.1.3.1 Preparation of fibre under test

Fibre ends shall be substantially clean, smooth, and perpendicular to the fibre axis. Measurements on uncabled fibres shall be carried out with the fibre loose on the drum, i.e., microbending effects shall not be introduced by the drum surface.

5.4.1.3.2 Procedure

1) The fibre under test is placed in the measurement set-up. The output power P_2 is recorded.

2) Keeping the launching conditions fixed, the fibre is cut to the cut-back length (for example, 2 m from the launching point). The cladding mode stripper, when needed, is refitted and the output power P_1 from the cut-back length is recorded.

3) The attenuation of the fibre, between the points where P_1 and P_2 have been measured, can be calculated, using P_1 and P_2, from the definition Equations 3-4 and 3-5.

5.4.1.4 Presentation of the results

a) Test set-up arrangement, including source type, source wavelength, and linewidth (FWHM).

b) Fibre identification.

c) Length of sample.

d) Attenuation of the sample quoted in dB.

e) Attenuation coefficient quoted in dB/km.

f) Indication of accuracy and repeatability.

g) Temperature of the sample and environmental conditions (if necessary).

5.4.2 First alternative test method: The backscattering technique

5.4.2.1 General

A test method for the attenuation coefficient of single-mode optical fibre based on bidirectional backscattering measurements is described. This technique can also be applied to check the attenuation uniformity, optical continuity, physical discontinuities, splice losses and the length of the fibre.

Unidirectional backscattering measurements can be adopted in particular cases, e.g., verification of the backscatter slope variation in cabled fibres.

Procedures for the calibration of backscattering equipment (for single-mode fibres) are provided in [IEC 61746-1].

5.4.2.2 Test apparatus

5.4.2.2.1 General considerations

The signal level of the backscattered optical signal will normally be small and close to the noise level. In order to improve the signal-to-noise ratio and the dynamic measuring range, it is therefore customary to use a high power light source in connection with signal processing of the detected signal. In addition, adjustment of the pulse width may be required to obtain a compromise between resolution and dynamic range.

Care must be taken that higher order modes do not propagate.

An example of apparatus is shown in Figure 14a.

5.4.2.2.2 Optical source

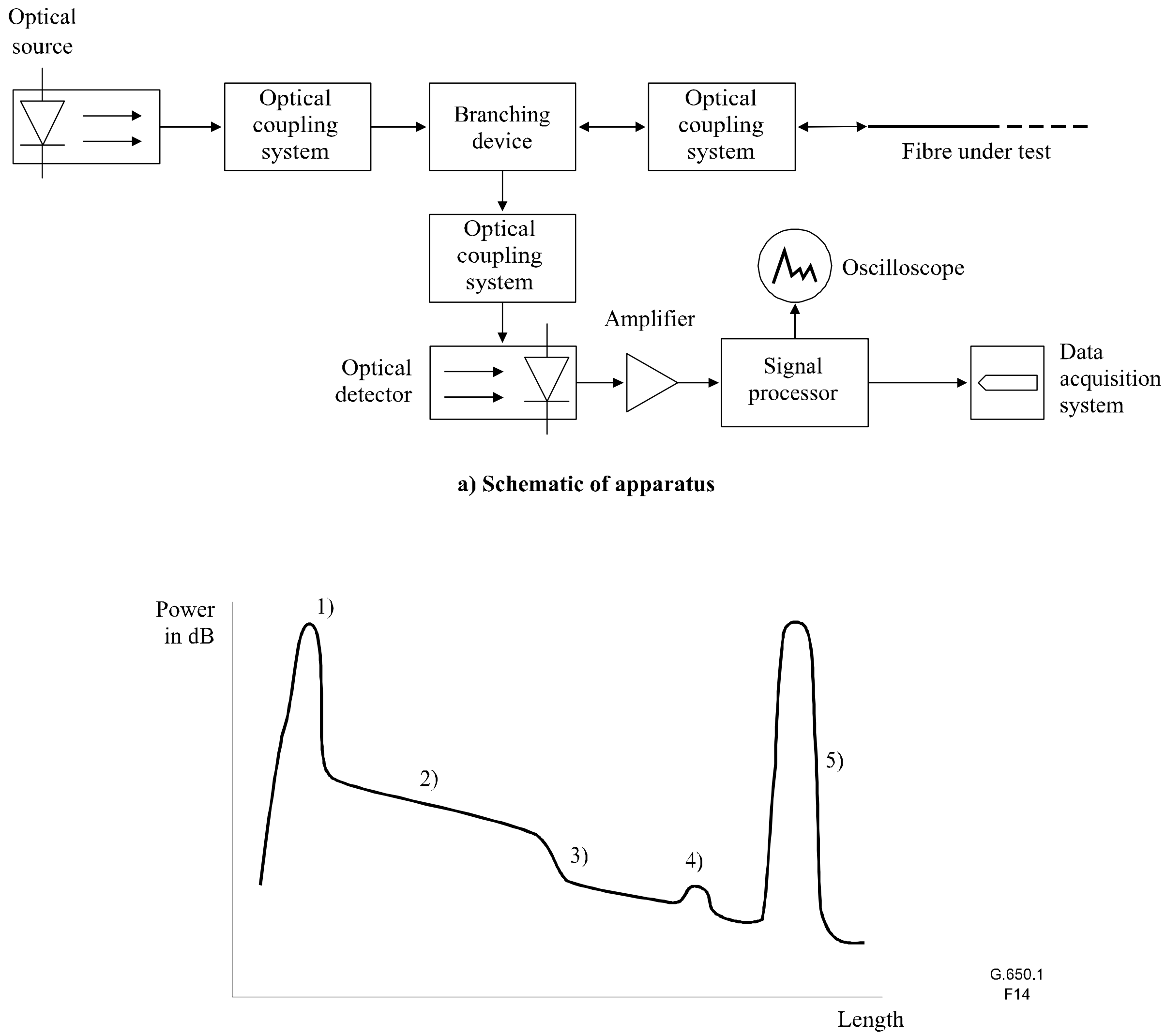
Use a stable, high power optical source of appropriate wavelengths and record them. The pulse width and repetition rate should be consistent with the desired resolution and the length of the fibre.

5.4.2.2.3 Optical coupling system

An optical system for an efficient coupling of the beam into the fibre under test, the branching device or the optical detector shall be used. Various devices, such as index matching materials, can be added to reduce Fresnel reflections.

5.4.2.2.4 Branching device

A branching device is needed to couple the source radiation into the fibre and the backscattered radiation onto the detector, while avoiding a direct source-detector coupling. Avoid using devices with polarization-dependent properties.



a) Schematic of apparatus

b) Example of a unidirectional backscattering loss curve

Figure 14 – The backscattering technique

5.4.2.2.5 Optical detector

A detector shall be used so that the maximum possible backscattered power is intercepted. The detector response shall be compatible with the levels and wavelengths of the detected signal. A substantially linear detector response is required for attenuation measurements.

5.4.2.2.6 Amplifier

A suitable amplifier shall follow the optical detector, so that the signal level becomes adequate for signal processing. The amplifier bandwidth should involve a trade-off between time resolution and noise reduction.

5.4.2.2.7 Signal processor

A signal processor able to improve the signal-to-noise ratio, to calculate the attenuation curve from the two unidirectional backscattering loss curves, and to provide a logarithmic response in the detection system is required. An oscilloscope for a direct view of the backscattering trace and a data acquisition system to store the measurement results can be connected to the signal processor.

5.4.2.2.8 Cladding mode stripper

See clause 5.4.1.2.5.

5.4.2.2.9 Fibre sample configuration

The measurement may be made with the fibre in a number of fibre configurations (e.g., as cabled fibre, on a suitable shipping spool or as required for the reference text method).

5.4.2.3 Measurement procedure

a) Align the fibre under test to the optical coupling system.

b) Measure two unidirectional backscattering loss curves, one from each end of the fibre. Figure 14b shows an example of such a unidirectional curve. Each backscattering loss curve is analysed by the signal processor and recorded on a logarithmic scale, avoiding the parts at the two ends of the curves, due to the reflections of the coupling and branching devices and by the fibre ends (see parts 1) and 5) in Figure 14b.

c) Evaluate the length, L_f, of the fibre from the time interval between the two ends of the backscattering loss curve, T_f, and the group delay index, N, of the fibre as: $L_f = c \cdot T_f / N$ (c being the free space light speed).

d) Obtain the bidirectional backscattering loss curve using the two measured and recorded unidirectional backscattering loss curves, according to the procedure outlined in the following:

Let a(x) and b(z) be the functions describing the two unidirectional backscattering loss curves expressed in dB, with x and z being the distances from the fibre ends nearest the respective launch site. The bidirectional backscattering loss curve is given by:

$$y(x) = \frac{a(x) - b(L_f - x)}{2} \qquad (5\text{-}14)$$

e) Obtain the end-to-end fibre attenuation coefficient according to the procedure outlined in the following:

The attenuation coefficient, $A(x_0, x_1)$, for a fibre segment defined by the end positions x_0 and x_1 (with $x_0 < x_1$) is given by:

$$A(x_0, x_1) = \frac{y(x_0) - y(x_1)}{x_1 - x_0} \qquad (5\text{-}15)$$

This expression may be evaluated by a least squares linear fit of the data between x_0 and x_1.

The end-to-end fibre attenuation coefficient is determined in the same way as Equation 5-15 with the data points as close as possible to the end positions. However, these points should be outside the dead zone area and the end reflection area (see Figure 14b, areas 1) and 5)).

5.4.2.4 Presentation of the results

a) Test set-up arrangement.

b) Kind of signal processing used.

c) Date of test.

d) Test specimen identification and length.

e) Pulse width.

f) Test wavelength(s).

g) End-to-end fibre attenuation coefficient in dB/km.

h) Bidirectional backscattering loss curve.

NOTE – Unidirectional backscattering measurements are obtained with the function a(x) alone. The complete analysis of the recorded unidirectional backscattering loss curves (Figure 14b) shows that, independently from the attenuation measurements, many phenomena can be monitored using the backscattering technique including:

1) Reflection originated by the branching and coupling devices at the input end of the fibre.
2) Zone of invariant backscattered slope.
3) Discontinuity due to local defect, splice or coupling.
4) Backscattering slope variation with length.
5) Fluctuation at the output end of the fibre.
6) Attenuation change, for example with temperature.

5.4.3 Second alternative test method: The insertion loss technique

5.4.3.1 General

The insertion loss technique consists of the evaluation of the power loss due to the insertion of the fibre under test between a launching and a receiving system, previously interconnected (reference condition). The powers P_1 and P_2 are thus evaluated in a less straightforward way than in the cut-back method. Therefore, this method is not intended for use on factory lengths of fibres and cables.

The insertion loss technique is less accurate than a cut-back one, but has the advantage of being non-destructive for the fibre under test and for the semi-connectors possibly fixed at both ends. Therefore, it is particularly suitable for field use, and mainly intended for use with connectorized cable lengths.

Two options are considered in the following for this technique (see Figure l5); they differ in the nature of the launching and receiving systems, as outlined below. Measurement conditions in between option a) and b) are possible and are discussed in Note 2 to clause 5.4.3.3.2.

In option a), the quality of the semi-connectors possibly fixed to the fibre under test (and in general the quality of the used interconnection devices) influences the results; in option b), this influence is nearly excluded. As a consequence, option b) has in general a better accuracy, and it is more suitable when the actual attenuation of the fibre alone is needed. Conversely, when the fibre section under test is fitted with semi-connectors and has to be cascaded with other elements, the results from option a) are more meaningful, as they take into account the deviation of the semi-connectors from the nominal loss.

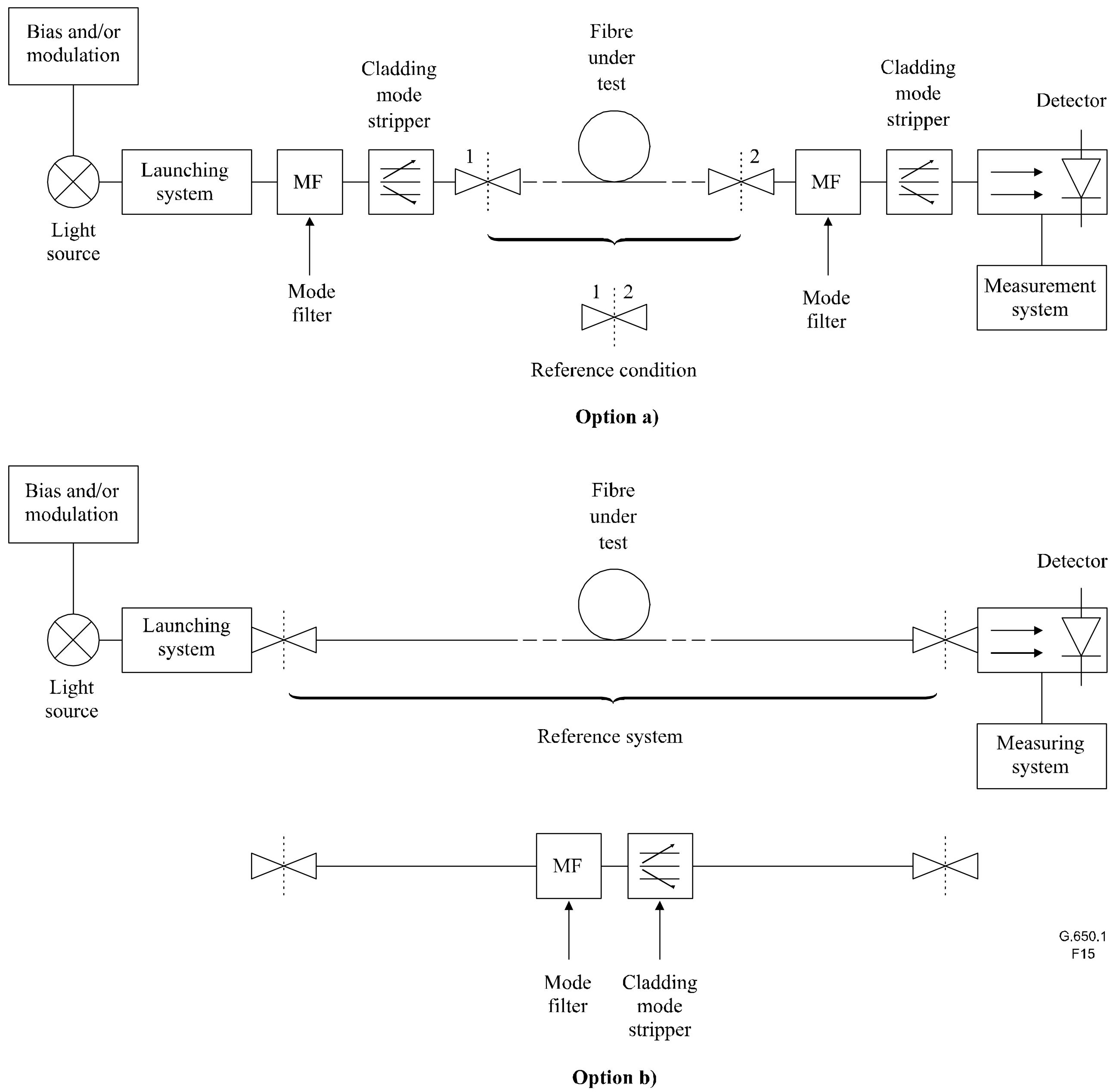


Figure 15 – Typical arrangements for the insertion loss technique

5.4.3.2 Test apparatus

The schematic diagram of the test apparatus is shown in Figure l5. Measurements may be made at one or more wavelengths, or alternatively, a spectral response may be required over a range of wavelengths.

5.4.3.2.1 Optical source

A suitable intensity stable radiation source shall be used, such as a lamp, a laser or a light emitting diode. If a broad spectrum source is used, it should be followed by a wavelength selection device (alternatively this device can be inserted before the detector). In every case, the nominal wavelength of the source (possibly taking into account the wavelength selection device) shall be known.

The spectral width (FWHM) should be narrow compared with any features of the fibre spectral attenuation.

5.4.3.2.2 Modulation

See clause 5.4.1.2.2.

5.4.3.2.3 Launching conditions

For option a)

The source is coupled to a short length of single-mode fibre having the same nominal characteristics of the fibre under test and equipped with a mode filter and a cladding mode stripper (see below).

The above single-mode fibre is coupled to the fibre under test with a very precise coupling device to minimize coupling losses and ensure meaningful results. If the fibre under test is equipped with a semi-connector, a compatible high quality semi-connector shall be fixed to the launching fibre.

For option b)

The source is coupled through a suitable optic to the fibre under test in such a way that the launched spot at the fibre input-end face has a near-field and a far-field intensity almost uniform within the mode field diameter and the far-field intensity of the fibre under test.

The system can employ lenses and a fibre positioner; alternatively, the light can be launched in a step-index multimode fibre to be connected to the fibre under test.

This is accomplished with any coupling device or a semi-connector compatible with those terminating the fibre under test.

5.4.3.2.4 Reference system (option b) only)

This system is composed of a short length of single-mode fibre having the same nominal characteristics of the fibre under test. The fibre is equipped with a mode filter and a cladding mode stripper; both devices shall not introduce any loss on the fundamental mode.

5.4.3.2.5 Mode filter

The mode filter shall allow the propagation along the fibre of the fundamental mode only. As an example, it can be implemented by a suitable bending condition on the fibre.

5.4.3.2.6 Cladding mode stripper

A cladding mode stripper encouraging the conversion of cladding modes to radiation modes should be employed. This device is not necessary if the fibre itself does not allow the propagation cladding modes.

5.4.3.2.7 Optical detection

The spectral response of the optical detector shall be compatible with the spectral characteristics of the source. It must have linear sensitivity characteristics.

For option a)

The detector is connected to a single-mode fibre having the same nominal characteristics of the fibre under test. The fibre should be equipped with a mode filter and a cladding mode stripper.

For the coupling with the fibre under test, the same indication as in clause 5.4.3.2.3, option a), is used.

For option b)

The end of the fibre under test is positioned in front of the detector.

A suitable detector shall be used so that all the radiation emerging from the fibre is intercepted. The detector should be spatially uniform.

Alternatively, the detector is connected to a step-index multimode fibre. This fibre is coupled to the fibre under test by any coupling device or a semi-connector compatible with those terminating the fibre under test.

5.4.3.3 Measurements procedure

5.4.3.3.1 Preparation of fibre under test

See clause 5.4.1.3.1.

If the fibre is fitted with connectors, an appropriate cleaning procedure is required.

5.4.3.3.2 Procedure

1) Once a measurement wavelength is selected, the power P_1 is firstly measured in the following way:

For option a)

The fibre of the launching system is connected to the fibre of the receiving system. The received power P_1 is then recorded.

For option b)

The reference system is connected between the launching and the receiving systems. The received power P_1 is then recorded.

2) Successively, the fibre under test is connected between the launching and the receiving systems. The received power P_2 is then recorded.

3) Finally, the attenuation A of the fibre section is calculated in the following way:

For option a)

$$A = 10\log\frac{P_1(\lambda)}{P_2(\lambda)} + C_r - C_1 - C_2 \text{(dB)} \qquad (5\text{-}16a)$$

where C_r, C_1, and C_2 are the nominal average losses (in dB) of the connections respectively in the reference conditions at the input of the fibre under test and at its output.

For option b)

$$A = 10\log\frac{P_1(\lambda)}{P_2(\lambda)} \text{(dB)} \qquad (5\text{-}16b)$$

NOTE 1 – The use of option b) assumes that the fibre under test does not allow the propagation to the receiving end of modes other than the fundamental one.

NOTE 2 – Fibre attenuation measurements are also possible with a hybrid test set-up, using a launching system as in option a) and a receiving system as in option b), or vice versa.

The measurement procedure for P_1 is in both cases similar to the one listed above for option a); no reference system is required and the launching system is connected directly to the receiving system.

In both cases the fibre section attenuation can be calculated as:

$$A = 10\log\frac{P_1(\lambda)}{P_2(\lambda)} - C_a \text{(dB)} \qquad (5\text{-}17)$$

where C_a is the nominal average loss (in dB) of the connection between the fibre under test and that part of the test set-up (launch or receive) belonging to option a).

NOTE 3 – The intrinsic capability of option a) to evaluate the semi-connectors behaviour does not imply its use whenever this evaluation is required.

Alternative possibilities are in using, even at an end where the semi-connector evaluation is required, an option b) set-up, previously connecting a single-mode cord to the fibre under test. The nominal loss of the fibre-to-cord connector is to be subtracted from the measured loss.

The test apparatus to be used in practice should be chosen to minimize the error sources, taking into account the available instrumentation and connecting devices. The use of a hybrid set-up (a-launch, b-receive) plus a cord at the receiving end is usually the best solution when both the semi-connectors have to be evaluated.

5.4.3.4 Presentation of the results

a) Test set-up arrangement, including source type, source wavelength, spectral width (FWHM) used for the measurement and the option type a) or b).

b) Fibre identification.

c) Length of the fibre section and end conditions (presence of semi-connectors).

d) Attenuation of the section quoted in dB.

e) Attenuation coefficient quoted in dB/km.

f) Indication of accuracy and repeatability (the connection loss repeatability shall be taken properly into account).

g) Temperature of the sample and environmental conditions (if necessary).

5.4.4 Third alternative test method: Spectral attenuation modelling

5.4.4.1 General

The attenuation coefficient of a fibre across a spectrum of wavelengths may be calculated by means of a characterizing matrix, M, and a vector, v. The vector contains the measured attenuation coefficients of a small number (three to five) of wavelengths (e.g., 1310 nm, 1360 nm, 1380 nm, 1410 nm, 1550 nm, and/or 1625 nm).

In one approach, the fibre or cable supplier shall provide a matrix characteristic of its product, and the modelled spectral attenuation is a vector, w, calculated from the product of M and v:

$$w = M \cdot v$$

Alternatively, if using a generic matrix, the supplier shall provide a correction-factor vector such that the prediction equation becomes:

$$W = w + e$$

where:

W is the modified vector

w comes from $w = M \cdot v$

e is the correction-factor vector

A generic matrix is a characterizing matrix which can be applied to a variety of fibres, designs, and suppliers (presumably within a single fibre type), and which is determined and/or invoked by a standards body, single customer/end-user, or other industry source to which individual suppliers can compare their products, the difference being resolved by the vector, e.

5.4.4.2 Test apparatus

Since this technique involves a calculation using previously determined values, there is no specific apparatus required. Any of the recommended test methods (clause 5.4.1 the cut-back technique; clause 5.4.2 the backscattering technique; clause 5.4.3 the insertion loss technique) may be used to generate the measured values upon which the calculations are made.

Direct measurements of attenuation take precedence over this method is the case of a conflict.

5.4.4.3 Calculation procedure

The attenuation coefficient of a fibre across a spectrum of wavelengths may be calculated from $w = M \cdot v$. The vector, v, contains the measured attenuation coefficients of a small number (three to five) of predictor wavelengths (e.g., 1310 nm, 1360 nm, 1380 nm, 1410 nm, 1550 nm, and/or 1625 nm) which were measured using one of the previous attenuation test methods. Multiplying the matrix, M, times the vector, v, yields another vector, w, which contains the predicted attenuation coefficients at many wavelengths (such as at 10 nm wavelength intervals from 1240 nm to 1600 nm).

The matrix, M, is given by:

$$
\begin{matrix}
A_{11} & A_{12} \ldots\ldots\ldots\ldots & A_{1n} \\
A_{21} & A_{22} \ldots\ldots\ldots\ldots & A_{2n} \\
" & " & \\
" & " & \\
" & " & \\
A_{m1} & A_{m2} \ldots\ldots\ldots\ldots & A_{mn}
\end{matrix}
$$

where m is the number of wavelengths where the attenuation coefficients have to be estimated, and n is the number of predictor wavelengths. An example of such a matrix is given for illustrative purposes in Appendix III.

The standard deviation of the difference between the actual and predicted attenuation coefficients at each wavelength is to be less than 0,xx dB/km within a stated wavelength range. A different tolerance – 0,yy dB/km – may be necessary if an additional wavelength range is specified. The values of xx and (yy), and the wavelength range(s) should be agreed upon between the user and the manufacturer.

If the estimate is obtained by using the supplier's specific matrix, M, then no correction vector, e, is necessary.

Since the elements of both M and e are achieved on a statistical basis, the w vector elements shall be determined as statistical. To indicate the accuracy of the predicted attenuation coefficients, the fibre suppliers shall give a vector containing the standard deviation of the differences between the actual and predicted attenuation coefficients, together with M and/or e (see clause 5.4.4.4).

NOTE 1 – In order to facilitate use of this matrix, the fibre should be routinely measured at the predictor wavelengths. The predictor wavelengths should number from 3 to 5, with a strong preference given to the lower number if sufficient accuracy can be achieved.

NOTE 2 – This model considers only uncabled fibre attenuation. An additional vector must be added to w to take account of cabling effects and environmental effects.

5.4.4.4 Presentation of the results

In addition to the items to be reported for the test method used in measuring the attenuation coefficients, report the following items:

a) The predicted attenuation and corresponding wavelength.

b) The method used to obtain the measured attenuation coefficient values (if requested).

c) The matrix used to predict the spectral attenuation, or the correction vector if a standard matrix was used (if requested).

d) The vector containing the standard deviation of the differences between the actual and predicted attenuation coefficients obtained during the development of the matrix (if requested).

5.5 Test methods for the chromatic dispersion

Chromatic dispersion varies with wavelength. Some methods and implementations measure the group delay as a function of wavelength and the chromatic dispersion and dispersion slope are deduced from the derivatives (with respect to wavelength) of this data. This differentiation is most often done after the data are fitted to a mathematical model. Other implementations of the reference method can allow direct measurement at each of the required wavelengths.

For some categories of fibre, the chromatic dispersion attributes are specified with the parameters of a specific model. In these cases, the relevant Recommendation defines the model appropriate for the definition of the specified parameters. For other fibre categories, the dispersion is specified to be within a given range for one or more specified wavelength intervals. In the latter case, either direct measurements may be made at the wavelength extremes or some fitting model may be used to either allow group delay measurement methods or implementations, or to allow storage of a reduced set of parameters that may be used to calculate the interpolated dispersion for particular wavelengths which may not have actual direct measurement values.

Annex A gives a general description of chromatic dispersion fitting and outlines a number of fitting equations suitable for use with any of the measurement methods or fibre categories.

5.5.1 Reference test method: The phase-shift technique

5.5.1.1 General

The fibre chromatic dispersion coefficient is derived from the measurement of the relative group delay experienced by the various wavelengths during propagation through a known length of fibre.

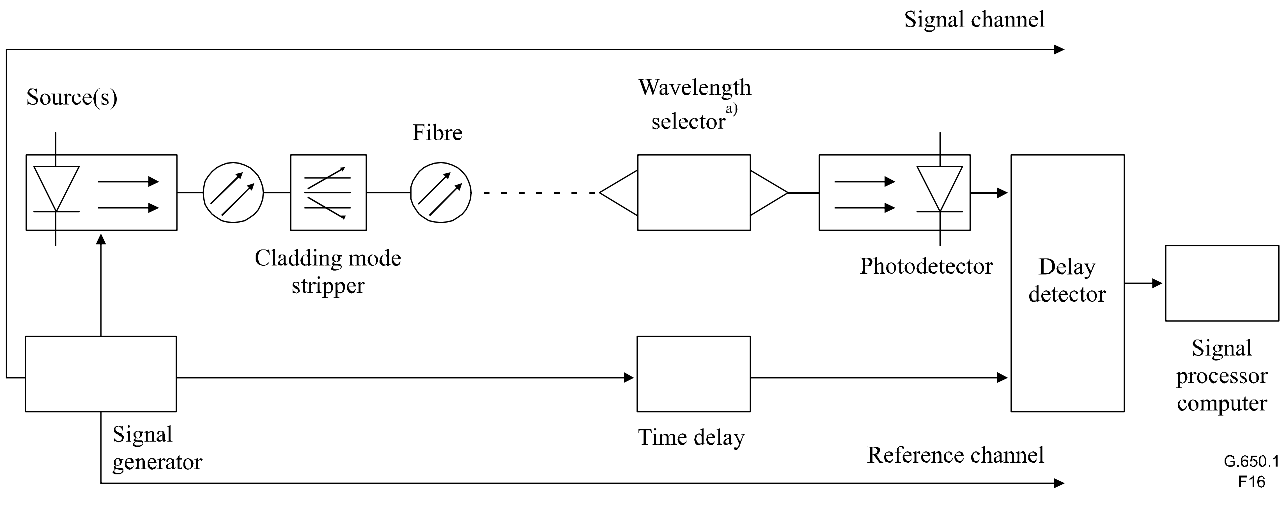
The group delay is measured in the frequency domain, by detecting, recording and processing the phase shift of a sinusoidal modulating signal.

The chromatic dispersion may be measured at a fixed wavelength or over a wavelength range.

NOTE – Differential phase shift is documented in [IEC 60793-1-42], Annex C.

5.5.1.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure l6.



a) When needed.

Figure 16 – Typical arrangement of the test apparatus

5.5.1.2.1 Optical source

The optical source shall be stable in position, intensity and wavelength over a time period sufficiently long to complete the measurement procedure. Laser diodes, (laser diode array

(LD-array)), wavelength tunable laser diodes (WTL) (e.g., an external cavity laser (ECL)), LEDs or broadband sources, (e.g., an Nd:YAG laser with a Raman fibre) may be used, depending on the wavelength range of the measurement.

In any case, the modulating signal shall be such as to guarantee a sufficient time resolution in the group delay measurement.

5.5.1.2.2 Wavelength selection

The wavelength selector and monitoring are used to select and monitor the wavelength at which the group delay is to be measured. As a wavelength selector, an optical switch, a monochromator, dispersive devices, optical filters, optical couplers, connectors may be used, depending on the type of light sources and measurement set-up. The selection may be carried out by switching electrical driving signals for different wavelength light sources.

The wavelength monitoring may be carried out by an optical fibre coupler and a wavelength meter. The wavelength selector and monitor may be used either at the input or at the output end of the fibre under test.

If a mathematical fit is made to the data, at least one data point must be within 100 nm of λ_0.

5.5.1.2.3 Detector

The light emerging from the fibre under test, the reference fibre or the optical divider, etc., is coupled to a photodetector whose signal-to-noise ratio and time resolution are adequate for the measurement. The detector is followed by a low noise amplifier if needed.

5.5.1.2.4 Reference channel

The reference channel may consist of electrical signal line or optical signal line. A suitable time delay generator may be interposed in this channel. In certain cases, the fibre under test itself can be used as the reference channel line.

5.5.1.2.5 Delay detector

The delay detector shall measure the phase shift between the reference signal and the channel signal. A vector voltmeter could be used.

5.5.1.2.6 Signal processor

A signal processor can be added in order to reduce the noise and/or the jitter in the measured waveform. If needed, a digital computer can be used for purposes of equipment control, data acquisition and numerical evaluation of the data.

5.5.1.3 Measurement procedure

The fibre under test is suitably coupled to the source and to the detector through the wavelength selector or the optical divider, etc. If needed, a calibration of the chromatic delay of the source may be performed. A suitable compromise between wavelength resolution and signal level must be achieved. Unless the fibre under test is also used as the reference channel line, the temperature of the fibre must be sufficiently stable during the measurement.

The phase shift between the reference signal and the channel signal at the operating wavelength are to be measured by the delay detector. Data processing appropriate to the type of modulation is used in order to obtain the chromatic dispersion coefficient at the operating wavelength. When needed, a spectral scan of the group delay versus wavelength can be performed; from the measured values a fitting curve can be completed.

The time group delay will be deduced from the corresponding phase shift ϕ through the relation $\tau = \phi/(2\pi f)$, f being the modulation frequency.

5.5.1.4 Presentation of the results

a) Test set-up arrangement.

b) Type of modulation used.

c) Source characteristics.

d) Fibre identification and length.

e) Characteristics of the wavelength selector (if present).

f) Type of photodetector.

g) Characteristics of the delay detector.

h) Model used to fit the relative group delay data or chromatic dispersion data, and the fitting wavelength range used.

i) Values of coefficients from the fit for each fitting wavelength range.

j) Temperature of the sample and environmental conditions (if necessary).

5.5.2 First alternative test method: The interferometric technique

5.5.2.1 General

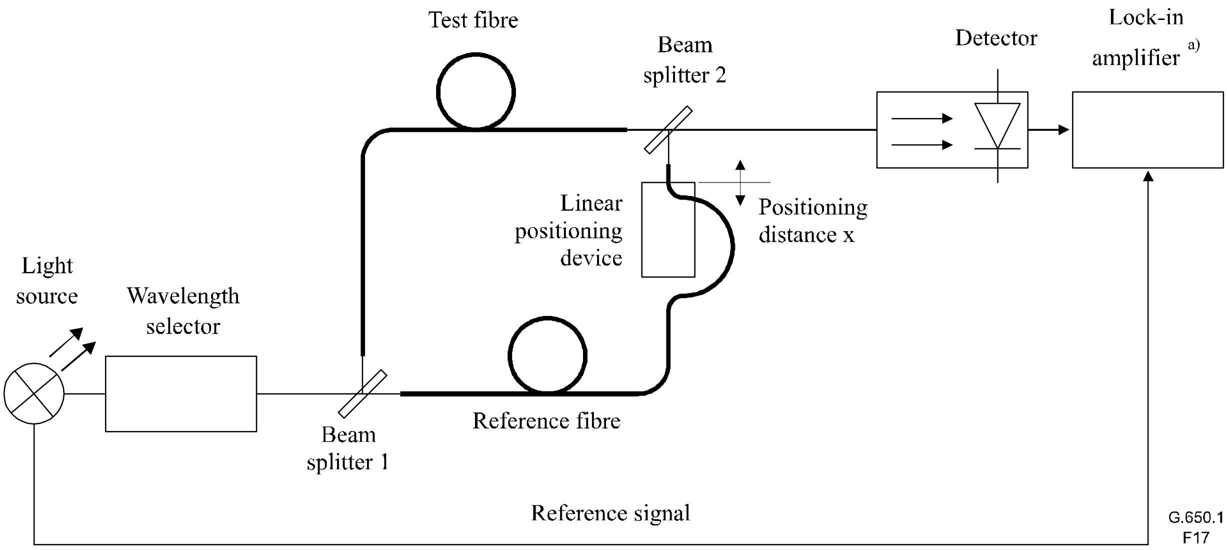
The interferometric test method allows the chromatic dispersion to be measured, using a short piece of fibre (several metres). This offers the possibility of measuring the longitudinal chromatic dispersion homogeneity of optical fibres. Moreover, it is possible to test the effect of overall or local influences, such as temperature changes and macrobending losses, on the chromatic dispersion.

According to the interferometric measuring principle, the wavelength-dependent time delay between the test sample and the reference path is measured by a Mach-Zehnder interferometer. The reference path can be an air path or a single-mode fibre with known spectral group delay.

It should be noted that extrapolation of the chromatic dispersion values derived from the interferometric test on fibres of a few metres length, to long fibre sections assumes longitudinal homogeneity of the fibre. This assumption may not be applicable in every case.

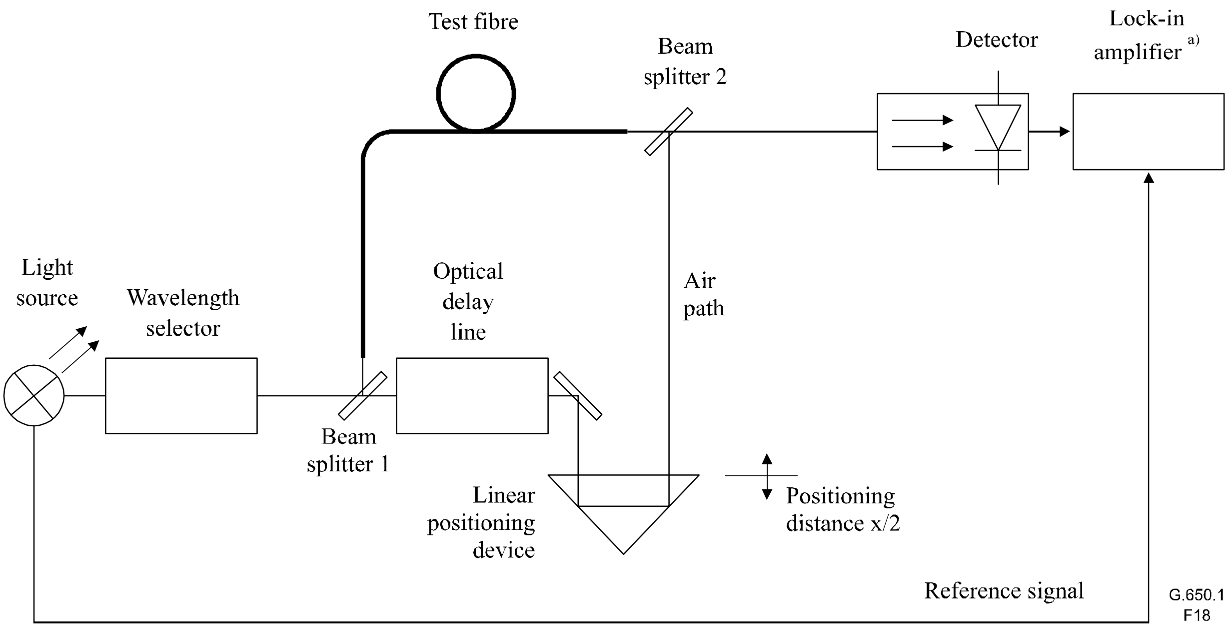
5.5.2.2 Test apparatus

Schematic diagrams of the test apparatus using a reference fibre and an air path reference are shown in Figures 17 and 18, respectively.



a) When needed.

Figure 17 – Schematic diagram of measurement set-up with reference fibre



a) When needed.

Figure 18 – Schematic diagram of measurement set-up with air path reference

5.5.2.2.1 Optical source

The source should be stable in position, intensity and wavelength for a time period sufficiently long to complete the measurement procedure. The source must be suitable, e.g., a YAG laser with a Raman fibre or a lamp and LED optical sources, etc. For the application of lock-in amplification techniques, a light source with low-frequency modulation (50 to 500 Hz) is sufficient.

5.5.2.2.2 Wavelength selector

A wavelength selector is used to select the wavelength at which the group delay is measured. A monochromator, optical interference filter, or other wavelength selector may be used depending on the type of optical sources and measurement systems. The wavelength selector may be used either at the input or the output end of the fibre under test.

The spectral width of the optical sources is to be restricted by the dispersion measuring accuracy, and it is about 2 to 10 nm.

If a mathematical fit is made to the data, at least one data point must be within 100 nm of λ_0.

5.5.2.2.3 Optical detector

The optical detector must have a sufficient sensitivity in that wavelength range in which the chromatic dispersion has to be determined. If necessary, the received signal could be upgraded with, for example, a transimpedance circuit.

5.5.2.2.4 Test equipment

For the recording of the interference patterns, a lock-in amplifier may be used. Balancing of the optical length of the two paths of the interferometer is performed with one linear positioning device in the reference path. Concerning the positioning device, attention should be paid to the accuracy, uniformity and stability of linear motion. The variation of the length should cover the range from 20 to 100 mm with an accuracy of about 2 µm.

5.5.2.2.5 Specimen

The specimen for the test can be uncabled and cabled single-mode fibres. The length of the specimen should be in the range 1 m to 10 m. The accuracy of the length should be about ±l mm. The preparation of the fibre endfaces should be carried out with reasonable care.

5.5.2.2.6 Data processing

For the analysis of the interference patterns, a computer with suitable software should be used.

5.5.2.3 Measurement procedure

1) The fibre under test is placed in the measurement set-up (Figures 17 and 18). The positioning of the endfaces is carried out with 3-dimensional micro-positioning devices by optimizing the optical power received by the detector. Errors arising from cladding modes are not possible.

2) The determination of the group delay is performed by balancing the optical lengths of the two interferometer paths with one linear positioning device in the reference path for different wavelengths. The difference between position x_i of the maximum of the interference pattern for wavelength λ_i and position x_0 for wavelength λ_0 (Figure 19) determines the group delay difference $\Delta\tau_g(\lambda_i)$ between the reference path and the test path as follows:

$$\Delta\tau_g(\lambda_i) = \frac{x_0 - x_i}{c_0} \quad (5\text{-}18)$$

where c_0 is the velocity of light in the vacuum. The group delay of the test sample is calculated by adding the value $\Delta\tau_g(\lambda_i)$ and the spectral group delay of the reference path. Dividing this sum by the test fibre length then gives the measured group delay difference per unit length $\tau(\lambda)$ of the test fibre.

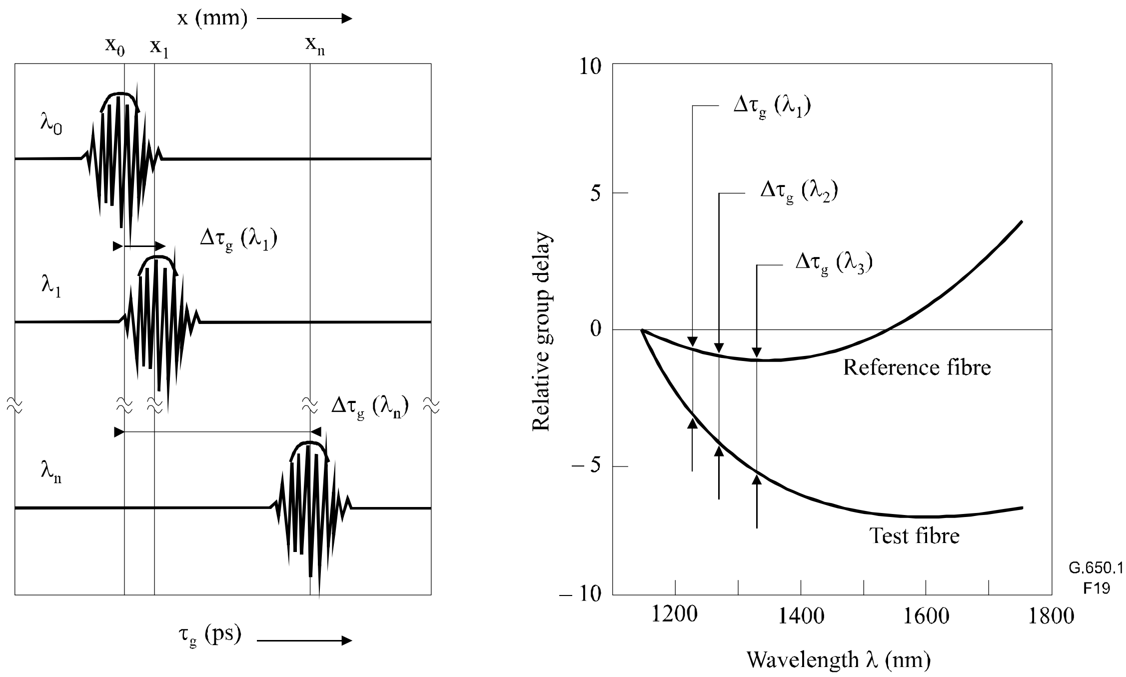


Figure 19 – Determination of the spectral group delay

5.5.2.4 Presentation of the results

a) Test set-up arrangement.

b) Source characteristics.

c) Fibre identification and length.

d) Characteristics of the wavelength selector (if present).

e) Type of the photodetector.

f) Model used to fit the relative group delay data or chromatic dispersion data, and the fitting wavelength range used.

g) Values of coefficients from the fit for each fitting wavelength range.

h) Temperature of the sample and environmental conditions (if necessary).

5.5.3 Second alternative test method: The pulse delay technique

5.5.3.1 General

The fibre chromatic dispersion coefficient is derived from the measurement of the relative group delay experienced by the various wavelengths during propagation through a known length of fibre.

The group delay is measured in the time domain, by detecting, recording and processing the delay experienced by pulses at various wavelengths.

The chromatic dispersion may be measured at a fixed wavelength or over a wavelength range.

5.5.3.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure 16.

5.5.3.2.1 Optical source

The optical source shall be stable in position, intensity and wavelength over a time period sufficiently long to complete the measurement procedure. Laser diodes, (laser diode array (LD-array)), wavelength tunable laser diodes (WTL) (e.g., an external cavity laser (ECL)), broadband sources (e.g., an Nd:YAG laser with a Raman fibre) may be used, depending on the wavelength range of the measurement.

In any case, the modulating signal shall be such as to guarantee a sufficient time resolution in the group delay measurement.

5.5.3.2.2 Wavelength selection

A wavelength selector and monitoring are used to select and monitor the wavelength at which the group delay is to be measured. As a wavelength selector, an optical switch, a monochromator, dispersive devices, optical filters, optical couplers, connectors may be used, depending on the type of light sources and measurement set-up. The selection may be carried out by switching electrical driving signals for different wavelength light sources.

The wavelength monitoring may be carried out by an optical fibre coupler and a wavelength meter. The wavelength selector and monitor may be used either at the input or at the output end of the fibre under test.

If a mathematical fit is made to the data, at least one data point must be within 100 nm of the zero-dispersion wavelength λ_0.

5.5.3.2.3 Detector

The light emerging from the fibre under test, the reference fibre or the optical divider, etc., is coupled to a photodetector whose signal-to-noise ratio and time resolution are adequate for the measurement. The detector is followed by a low noise amplifier if needed.

5.5.3.2.4 Reference channel

The reference channel may consist of electrical signal line or optical signal line. A suitable time delay generator may be interposed in this channel. In certain cases, the fibre under test itself can be used as the reference channel line.

5.5.3.2.5 Delay detector

The delay detector shall measure the delay time between the reference signal and the channel signal. A high-speed oscilloscope or a sampling oscilloscope could be used.

5.5.3.2.6 Signal processor

A signal processor can be added in order to reduce the noise and/or the jitter in the measured waveform. If needed, a digital computer can be used for the purposes of equipment control, data acquisition and numerical evaluation of the data.

5.5.3.3 Measurement procedure

The fibre under test is suitably coupled to the source and to the detector through the wavelength selector or the optical divider, etc. If needed, a calibration of the chromatic delay of the source may be performed. A suitable compromise between wavelength resolution and signal level must be achieved. Unless the fibre under test is also used as the reference channel line, the temperature of the fibre must be sufficiently stable during the measurement.

The time delay between the reference signal and the channel signal at the operating wavelength are to be measured by the delay detector. Data processing appropriate to the type of modulation is used in order to obtain the chromatic dispersion coefficient at the operating wavelength. When needed, a spectral scan of the group delay versus wavelength can be performed; from the measured values a fitting curve can be completed.

5.5.3.4 Presentation of the results

a) Test set-up arrangement.

b) Type of modulation used.

c) Source characteristics.

d) Fibre identification and length.

e) Characteristics of the wavelength selector (if present).

f) Type of photodetector.

g) Characteristics of the delay detector.

h) Model used to fit the relative group delay data or chromatic dispersion data, and the fitting wavelength range used.

i) Values of coefficients from the fit for each fitting wavelength range.

j) Temperature of the sample and environmental conditions (if necessary).

5.6 Test methods for the macrobend loss

5.6.1 Reference test method: Fibre winding

5.6.1.1 General

The macrobending loss measurement is intended to provide a means whereby certain loss values under different curvature radius to evaluate the macrobending performance of single-mode fibres.

NOTE – "curvature radius" is defined as the radius of the suitable circular shaped support (e.g., mandrel or guiding groove on a flat surface) on which the fibre can be bent.

5.6.1.2 Measurement considerations

5.6.1.2.1 Sample length

The specimen shall be a known length of fibre, as specified in the detail specification. In particular, the length of the sample tested for loss is determined by the measurement set-up, i.e., curvature radius (R) and number of turns (N); any further fibre length does not affect the measurement results, provided that the signal-to-noise (S/N) ratio is optimized.

5.6.1.2.2 Number of coils

The number of coils should be in accordance with the values stated in the relevant [ITU-T G.652], [ITU-T G.653], [ITU-T G.654], [ITU-T G.655], [ITU-T G.656] and [ITU-T G.657].

For single-mode fibres, the attenuation increases in a linear fashion with the number of coils.

For each radius, the number of coils shall be chosen in such a way that:

a) the induced loss is significantly higher than the detection limit of the set-up; when necessary, e.g., for low bend loss fibres, tests may be carried out with more coils than the specification requires – followed by linear normalization to the specified number;

b) the induced loss is significantly lower than the onset of the non-linear region in the set-up; for bending radii in the range 5 to 10 mm this may imply that not more than 5 to 10 coils should be used.

5.6.1.2.3 Bend radius

The value of bend radius shall be in accordance with the values stated in the relevant [ITU-T G.652], [ITU-T G.653], [ITU-T G.654], [ITU-T G.655], [ITU-T G.656] and [ITU-T G.657]. It should be considered that the macrobending losses increase exponentially as radius decreases.

NOTE – Further information on the relationship between macrobending losses and radius can be found in Annex A of [IEC 60793-1-47].

5.6.1.2.4 Measurement wavelength

The measurement wavelength shall be 1550 nm or 1625 nm, in accordance with the relevant [ITU-T G.652], [ITU-T G.653], [ITU-T G.654], [ITU-T G.655], [ITU-T G.656] and

[ITU-T G.657]. It should be considered that macrobending losses increase exponentially with the wavelength.

NOTE 1 – As optical bending losses of single-mode fibres increase with wavelength, a loss specification at the highest envisioned wavelength, i.e., either 1550 or 1625 nm, suffices. If required, customer and supplier can agree on a lower or higher specification wavelength.

NOTE 2 – Further information on the relationship between macrobending losses and measurement wavelength can be found in Annex A of [IEC 60793-1-47].

5.6.1.3 Test apparatus

The apparatus consists of a bending tool and a loss-measurement instrument.

5.6.1.3.1 Bending tool

The bending tool is used to hold the sample bent with a radius as stated in the specification. A mandrel or a guiding groove on a flat surface is applicable.

Since the actual curvature radius is critical, a maximum tolerance of ± 0.1 mm (for radii lower than or equal to 15 mm) or ± 0.5 to 1.0 mm (for larger radii) is accepted (a tighter tolerance on small radii is required for the higher measurement sensibility).

The test can be carried out on samples either making complete (360°) turn(s) in open air or around a suitable support (mandrel), or making u-turn(s) (180°) in open air or around suitable supports; the length under test is different in the two configurations, the length of a complete turn being twice the length of a u-turn. In the following, the term "coil" refers to one complete turn: one "coil" is made by two consecutive "u-turns" 3. This should be taken into account when normalizing the results to the length of the sample (number of coils).

5.6.1.3.2 Loss measurement instrument

The loss-measurement instrument uses either the transmitted power monitoring technique (method A of [IEC 60793-1-46]) or the cut-back technique (as in clause 5.4.1), taking care of the appropriate launch condition for the specific fibre type.

5.6.1.4 Measurement procedure

Prepare a flat end face, orthogonal to the fibre axis, at the input and output ends of each test specimen.

Loosely wind the fibre on the tool, avoiding excessive fibre twist. The number of turns, curvature radius and wavelength at which loss is to be measured are discussed in the following paragraphs.

Optical powers can be measured in the following two ways:

a) the power-monitoring technique, which measures the fibre attenuation increase due to a change from the straight condition to a bent condition; or

b) the cut-back technique, which measures the total attenuation of the fibre in the bent condition. In order to determine the induced attenuation due to macrobending, this value should be corrected for the intrinsic attenuation of the fibre.

The fibre length outside the mandrel and the reference cut-back length shall be free of bends that might introduce a significant change in the measurement result. Collection of excess fibre in a bend radius of at least 140 mm is recommended.

It is also possible to rewind the fibre from a mandrel with a large radius (introducing negligible macrobend loss) to the mandrel with the required radius. In this case, the macrobend loss can be determined directly by using the power-monitoring technique (without the correction for the intrinsic attenuation of the fibre).

Care must be taken in order not to introduce torsion on any fibre part during the measurements, as this would affect the result.

5.6.1.5 Calculation

The results are reported in dB as:

$$Loss(dB) = 10\log_{10}\left(\frac{P_{str}}{P_{Bend}}\right) \quad (5\text{-}19)$$

where P_{str} is the power measured without the bend and P_{Bend} is the power measured with the bend present.

NOTE 1 – The power through the straight fibre can be calculated from the fibre attenuation coefficient, the length tested, and the output power of the source.

NOTE 2 – For single-mode fibre, the loss can be reported in dB/turn.

5.6.1.6 Presentation of the results

a) Test set-up arrangement.

b) Fibre identification.

c) Length of specimen.

d) Macrobend radius.

e) Number of coils.

f) Wavelength(s) of interest.

g) Macrobending loss (dB) or (dB/turn).

5.7 Test methods for prooftesting

5.7.1 Reference test method: Longitudinal tension

5.7.1.1 General

a) This test method describes procedures for briefly applying tensile loads to an entire continuous length of fibre. The initial length may break into several shorter lengths, and each shorter length is considered to have passed the prooftest. An informative background can be found in [b-IEC/TR 62048].

b) Prooftesting is performed during fibre manufacturing, on-line as part of the fibre drawing and coating process, or off-line as part of the testing process. A break rate (failure per unit length) is statistically expected.

c) Standard ambient environmental conditions are used for storage and prooftesting: 23 ± 5°C and 50 ± 20% relative humidity. The storage time prior to prooftesting is an item for further study.

d) Either stress σ or strain ε may be used in the measurement. They are related by:

$$\sigma = E_0(1 + c_s\varepsilon)\varepsilon \quad (5\text{-}20)$$

where E_0 is Young's modulus at zero stress, and c_s is a parameter (typically between 3 and 6). The determination of parameters E_0 and c_s, if needed, is an item for further study.

e) The fibre stress is calculated from the applied tension, T, as:

$$\sigma = \frac{(1 - F)T}{\pi a^2} \quad (5\text{-}21)$$

where 2a is the diameter of the glass fibre and F is the fraction of the tension borne by the coating. F is given by:

$$F = \frac{\sum_{j+1}^{n} E_j A_j}{E_g \pi a^2 + \sum_{j=1}^{n} E_j A_j} \qquad (5\text{-}22)$$

n is the number of coating layers

E_j is the modulus of the jth coating layer

A_j is the nominal cross-sectional area of the jth coating layer

E_g is the modulus of the glass fibre

NOTE 1 – Coating moduli are typically characterized by manufacturers.

NOTE 2 – In case of strain controlled braked capstan prooftest machines, this compensation for the load sharing by the coating is not applicable.

5.7.1.1.1 Prooftest parameters

a) The proofstress, σ_p, is specified to control the length of the surviving sections of the fibre. The stress applied during the prooftest, σ_a, is illustrated in Figure 20. The load and unload times, t_l and t_u, and the dwell-time, t_d, are also shown. The tensile load shall be applied for as short a time as possible, yet sufficiently long to ensure the glass experiences the proofstress, typically much less than one second.

b) The applied stress shall exceed the specified proofstress at all times. The unload time shall be controlled to be less than some maximum values to be agreed between user and manufacturer to control unloading damage.

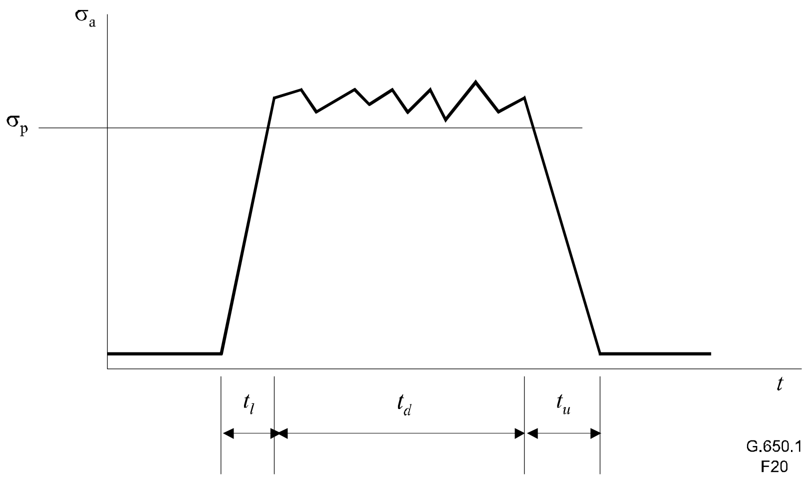


Figure 20 – Stress σ versus time *t* during prooftesting

5.7.1.2 Test apparatus

5.7.1.2.1 Operating procedure requirements

a) In the pay-out and take-up regions, the fibre is maintained with a low value of stress typically not exceeding 10% of the proofstress (see Figure 20).

b) In the loading region, fibre stress ramps up from a low stress level to the full proofstress. The load time is t_l.

c) In the prooftest region, the applied proofstress, σ_a, is maintained at values greater than the specified proofstress, σ_p.

d) In the unloading region, fibre stress ramps down from the applied stress to a low value of stress. The time to unload the fibre is t_u.

e) The unloading time is controlled to be less than a maximum value to be agreed between user and manufacturer. It can be varied by changing the processing speed or by the gripping capstan design.

f) The capstans and other support pulleys shall be designed and operated to ensure that they do not induce excessive damage. The gripping capstans shall be capable of maintaining the applied stress without inducing additional damage from slipping.

5.7.1.2.2 Prooftest machines

There are several possible machine designs, all of which perform the basic functions required for measuring fibre proof with the indicated general operating requirements. Care should be used in the design so as to prevent coating damage.

Two machine types are used:

– braked-capstan machine;

– dead-weight machine.

Either machine may be used during the fibre-drawing process (on-line for coated fibre only), or as a separate process step (off-line).

NOTE – There are dynamics with on-line screening, which are different from off-line screening, which should be taken into account.

a) *Braked-capstan machine* (Figure 21)

The fibre is paid out with constant, low tension. Also the rewinding after the prooftest is done with constant tension. The levels of the pay-off and take-up tensions are adjustable.

The prooftest load is applied to the fibre between the brake and drive capstans by creating a speed difference between the capstans. Two belts are used to prevent slippage at the capstans. One design can be that the high precision tension gauge measures the load on the fibre and controls the speed difference to achieve the required prooftest load. The load level and operating speed of the equipment can be independently set. Another design can be that the difference in speeds between the two capstans is set and controlled directly according to the desired fibre elongation (strain), without tension measurements.

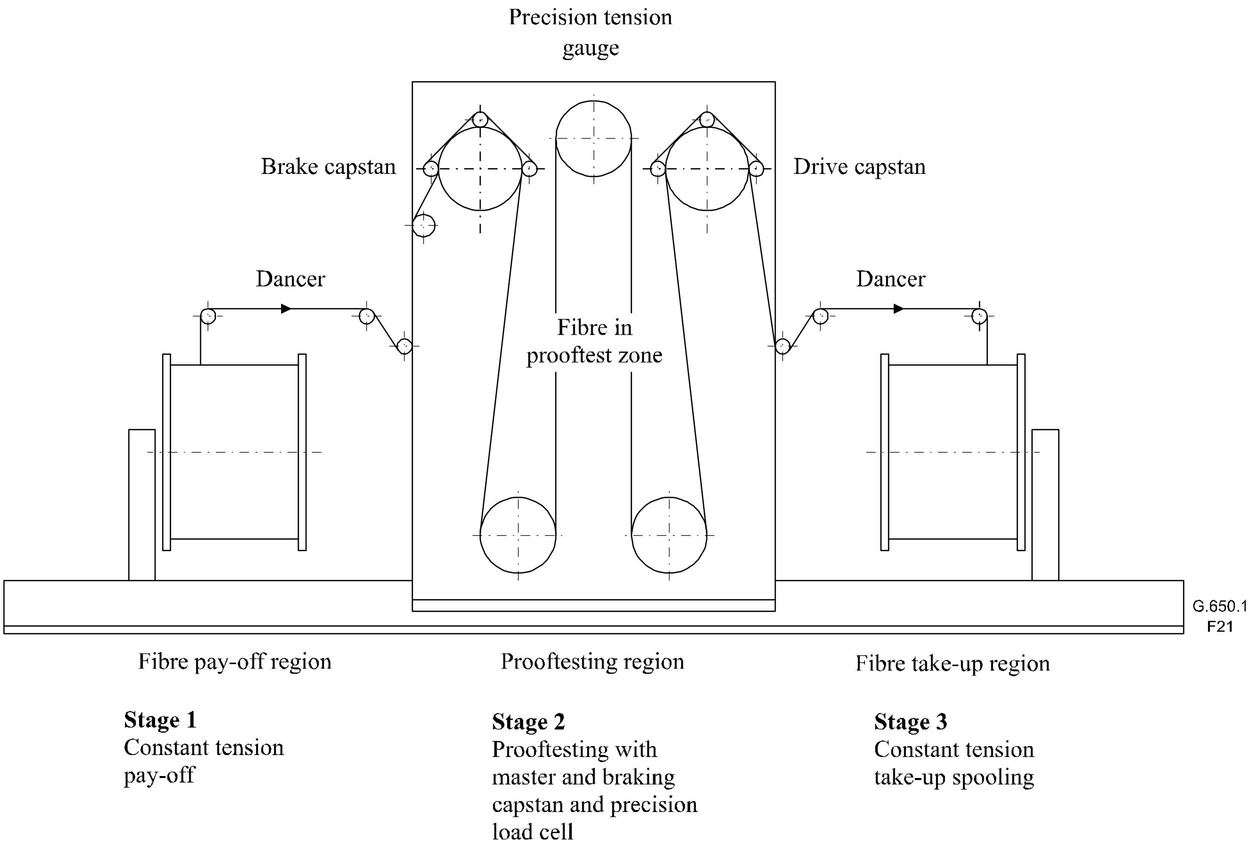


Figure 21 – Typical arrangement of a braked-capstan prooftest machine

b) *Dead-weight machine* (Figure 22)

The pay-out dancer and the take-up dancer pulleys are light enough to guide the fibre with minimal tension. The pay-out capstan and the take-up capstan are synchronized with each other. The capstan pinch belts prevent slippage at the capstans, but without additional stress to the fibre or damage to the fibre coatings. A load-arm and a dead-weight on a plate are attached to the shaft of a dead-weight dancer pulley to provide the proofstress to the fibre. An optional idler pulley provides an increased fibre gauge length if needed.

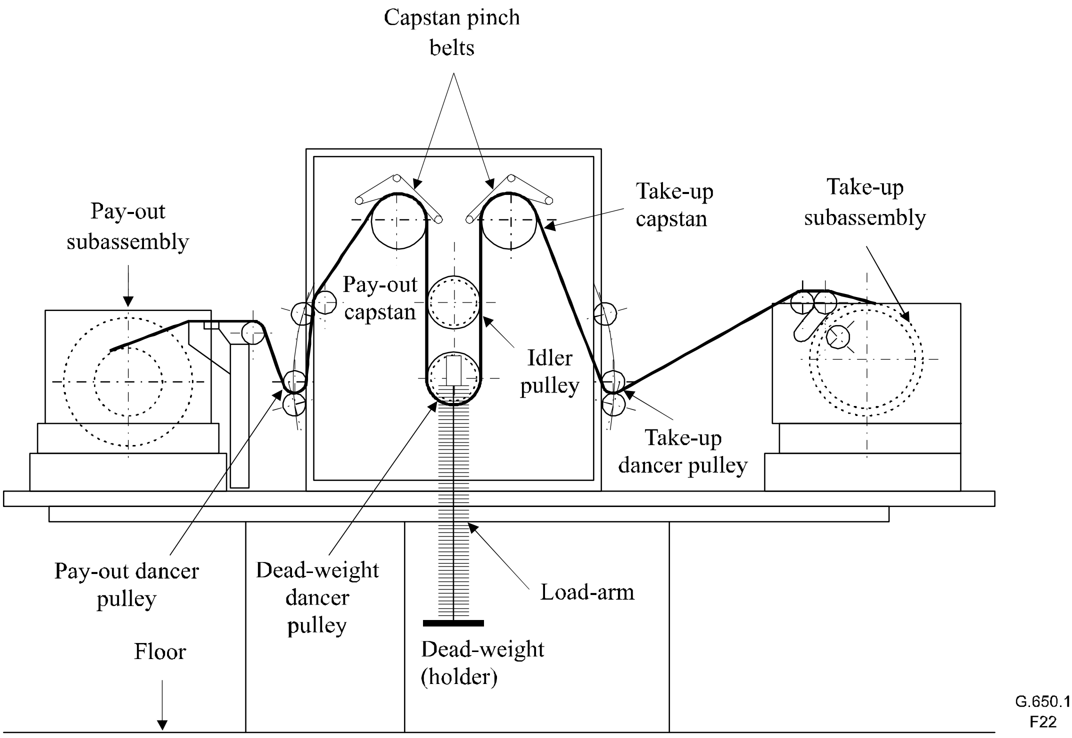


Figure 22 – Dead-weight prooftest machine

5.7.1.3 Measurement procedure

5.7.1.3.1 Sample

a) The test sample shall consist of the entire length of optical fibre, minus short sections at the ends in which all requirements, i.e., maximum unloading time, may not be met. This end allowance length, typically 25 m to 50 m, shall be presented.

b) Fibre failure after prooftesting shall be evidenced by complete breakage. Examination methods include visual inspection and OTDR measurements. After broken areas are removed, the surviving fibre lengths are considered to have passed the prooftest procedure.

5.7.1.3.2 Calculation

If the machine is calibrated in tension, the stress is calculated from Equation 5-21. Strain may be obtained from Equation 5-20.

5.7.1.4 Presentation of the results

a) General description of the apparatus.

b) Fibre identification.

c) Average applied proofstress.

d) Maximum unloading time.

e) Dwell-time.

f) End allowance length.

Annex A

Chromatic dispersion fitting

(This annex forms an integral part of this Recommendation)

A.1 General

The output from the measurement of chromatic dispersion is either directly measured chromatic dispersion values or group delay values as a function of wavelength. The chromatic dispersion value and dispersion slope is found from the derivatives of these data. The differentiation is most often done after the data are fitted to a mathematical model.

This annex gives a general description of chromatic dispersion fitting and outlines a number of standard fitting equations.

NOTE – Even though dispersion slope characteristics may not be normative requirements, typical values are often provided by manufacturers for ease in dispersion accommodation.

A.2 Definition of equations and fitting coefficients

Table A.1 contains a general description of mathematical models that are fitted. The polynomial formulation is general and can be extended to higher order polynomials via the same principles.

Table A.2 shows the corresponding equations for dispersion slope.

Table A.3 shows the formulae for the zero-dispersion wavelength and slope at that wavelength for the 3-term Sellmeier and second-order polynomial models.

Table A.1 – Definition of fit types and fit coefficients

Fit type	Equation for group delay	Equation for dispersion data
3-term Sellmeier	$A + B \cdot \lambda^2 + C \cdot \lambda^{-2}$	$2 \cdot B \cdot \lambda - 2 \cdot C \cdot \lambda^{-3}$
5-term Sellmeier	$A + B \cdot \lambda^2 + C \cdot \lambda^{-2} + D \cdot \lambda^4 + E \cdot \lambda^{-4}$	$2 \cdot B \cdot \lambda - 2 \cdot C \cdot \lambda^{-3} + 4 \cdot D \cdot \lambda^3 - 4 \cdot E \cdot \lambda^{-5}$
2nd order polynomial (quadratic)	$A + B \cdot \lambda + C \cdot \lambda^2$	$B + 2 \cdot C \cdot \lambda$
3rd order polynomial (cubic)	$A + B \cdot \lambda + C \cdot \lambda^2 + D \cdot \lambda^3$	$B + 2 \cdot C \cdot \lambda + 3 \cdot D \cdot \lambda^2$
4th order polynomial	$A + B \cdot \lambda + C \cdot \lambda^2 + D \cdot \lambda^3 + E \cdot \lambda^4$	$B + 2 \cdot C \cdot \lambda + 3 \cdot D \cdot \lambda^2 + 4 \cdot E \cdot \lambda^3$

Table A.2 – Slope equations

Fit type	Equation for dispersion slope
3-term Sellmeier	$2 \cdot B + 6 \cdot C \cdot \lambda^{-4}$
5-term Sellmeier	$2 \cdot B + 6 \cdot C \cdot \lambda^{-4} + 12 \cdot D \cdot \lambda^2 + 20 \cdot E \cdot \lambda^{-6}$
2nd order polynomial (quadratic)	$2 \cdot C$
3rd order polynomial (cubic)	$2 \cdot C + 6 \cdot D \cdot \lambda$
4th order polynomial	$2 \cdot C + 6 \cdot D \cdot \lambda + 12 \cdot E \cdot \lambda^2$

Table A.3 – Zero-dispersion wavelength and slope equations

Fit type	Zero-dispersion wavelength	Zero-dispersion slope
3-term Sellmeier	$(C/B)^{1/4}$	8B
2nd order polynomial (quadratic)	–B/(2C)	2C

A.3 Fitting procedure

For robust numerical fitting, the natural abscissa (wavelengths) should be converted to values with a reduced range by a change of coordinates before completing the least squares regression. After the regression, the fitting parameters must be converted back to the original wavelength scale before completing any of the derivatives.

A suitable implementation of least squares regression should be chosen to solve the fitting problem. The method should be stable towards noise and other errors introduced during the measurement of the group delay or dispersion data. (See, e.g., [b-Press].) Depending on the source of the input data, equations for group delay or the derivative dispersion is used.

Care should be taken to include a sufficient number of points in the fitting. When the fitting order and the number of points become comparable, the fitting will not yield accurate results.

If the fit is made to group delay data, chromatic dispersion data can be calculated from the dispersion equations in Table A.1, using the coefficients found from the fit. Extrapolation to wavelengths outside the fitting region should be used carefully, as the fits might have unphysical behaviour at points outside the region.

Dispersion slope can be calculated from the equations in Table A.2, using the coefficients found from the fit.

Appendix I

Methods of cut-off wavelength interpolation

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

This appendix presents methods of determining the coefficients, A_t and B_t found in clause 5.3.1.3.4, Equation 5-11.

I.1 Limited negative error method

The algorithm is derived from the observation that the transition structures (humps) consist of data points with a positive deviation from the expected ideal curve. The interpolation procedure is based on a theoretical model of the LP_{11} transition region and a method of fitting the data to the model. The procedure has six steps.

The first two steps define the LP_{01} region, or upper wavelength region. The second two steps define the transition region, where LP_{11} attenuation begins to increase. The fifth step characterizes this region according to a theoretical model. The last step computes the cut-off wavelength, λ_c, from the characterization parameters.

Step 1 – Define the upper wavelength region

Lower wavelength of the region

For multimode reference:

Find the maximum slope wavelength, the wavelength at which the first difference $a(\lambda) - a(\lambda + 0.01)$, is largest. For wavelengths greater than the maximum slope wavelength, the lower wavelength of the region is the wavelength at which the attenuation is minimum.

For bend reference, the following simulates the procedure for multimode reference:

Find the maximum attenuation wavelength. For wavelengths greater than the maximum attenuation wavelength, the lower wavelength of the region is the wavelength at which the following function is minimum:

$$a(\lambda) - 8 + 8\lambda \ \ (\lambda \text{ in } \mu\text{m})$$

Upper wavelength of the region

Lower wavelength of region plus 0.15 μm.

Step 2 – Characterize the attenuation curve, a(λ), of the upper wavelength region as a linear equation in wavelength, λ

$$a(\lambda) \cong A_u + B_u \lambda \tag{I-1}$$

The following approaches are suggested:

Bend reference method:

Set $B_u = 0$

Set A_u = median of attenuation values in the upper wavelength region.

Multimode reference method:

Find A_u and B_u such that the sum of the absolute values of error in the upper wavelength region is minimum and such that all errors are non-negative. Find the median of the errors in the upper wavelength region and add to A_u.

Determine the most negative error of the upper wavelength region, E:

$$E = \min[a(\lambda) - A_u - B_u\lambda] \quad \text{(I-2)}$$

Step 3 – Find the upper wavelength of the transition region

Starting at the upper wavelength of the upper wavelength region, from Step 1, determine the maximum wavelength at which the attenuation is 0.1 dB greater than the line found in Step 2. Set the upper wavelength of the transition region to this value plus 10 nm.

Step 4 – Find the lower wavelength of the transition region

There are various methods to determine this wavelength. The following are examples:

Let:

$$\Delta a(\lambda) = a(\lambda) - A_u - B_u(\lambda) \quad \text{(I-3)}$$

a) Starting with the upper wavelength of the transition region, from Step 3, find the wavelength at which Δa(λ) has a local maximum and so the difference between this maximum and the next local minimum (at larger λ) is maximum.

b) The largest wavelength, below the upper wavelength of the transition region, such that:

Δa(λ) is greater than 2 dB; and

b1) There is a local maximum for Δa(λ); or

b2) There is a local maximum for Δa(λ) – Δa(λ + 0.01).

Step 5 – Characterize the transition zone with the model and constraints on errors

The model is a linear regression of a transformation. Constraints on errors control negative regression errors so that the inverse transform of the fitted line will not produce negative attenuation errors less than E, from Step 2. Fitting the data with constraints on errors may be done with simplex linear programming methods.

Find A_t and B_t, from clause 5.3.1.3.4, Equation 5-11, such that the sum of the absolute values of error is minimized and such that no error is less than –v(λ), with v(λ) given as a function of E, from Step 2:

$$w(\lambda) = 10^{\frac{\Delta a(\lambda) - E}{10}} \quad \text{(I-4)}$$

$$z(\lambda) = 10\log\left[-\frac{10}{A}\log\left(\frac{w(\lambda)-1}{\rho}\right)\right] \quad \text{(I-5)}$$

$$v(\lambda) = Y(\lambda) - z(\lambda) \quad \text{(I-6)}$$

Step 6 – Evaluate the slope of the transition and compute the cut-off wavelength, λ_c

If B_t is greater than some small negative value, e.g., –1 to –0.1, reduce the upper wavelength of the transition region by 10 nm and repeat Step 5.

Otherwise, compute λ_c:

$$\lambda_c = -\frac{A_t}{B_t} \quad \text{(I-7)}$$

I.2 Least squares method

This algorithm is based on the assumption that the structure sometimes seen in the transition region is caused by an interference effect around the position of the ideal curve.

The mathematical model is the same as used in the limited negative error method.

Step 1 – As limited negative error method.

Step 2 – As limited negative error method. E in Equation (I-2) is not required.

Step 3 – As limited negative error method.

Step 4 – As limited negative error method.

Step 5 – Characterize the transition zone.

The model is a least squares best fit of a transformation.

Find A_t and B_t from clause 5.3.1.3.4, Equation 5-11, such that the sum of the squares of the errors is minimized, using Equations 5-8, 5-9, 5-10 and:

$$W(\lambda) = 10^{\Delta a(\lambda)/10} \quad \text{(I-8)}$$

Step 6 – As limited negative error method.

Appendix II

Test method for measuring chromatic dispersion uniformity based on the backscattering technique

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

II.1 General

A test method is described by which to determine the uniformity of the chromatic dispersion of a single-mode optical fibre based on bidirectional backscattering measurements. This technique can evaluate the uniformity of the waveguide and material dispersion individually. Moreover, this technique can be used to measure the mode field diameter. Procedures for the calibration of backscattering equipment are provided in [IEC 61746-1].

II.2 Test apparatus

II.2.1 General considerations (as in clause 5.4.2.2.1)

An example of the apparatus is shown in Figure II.1.

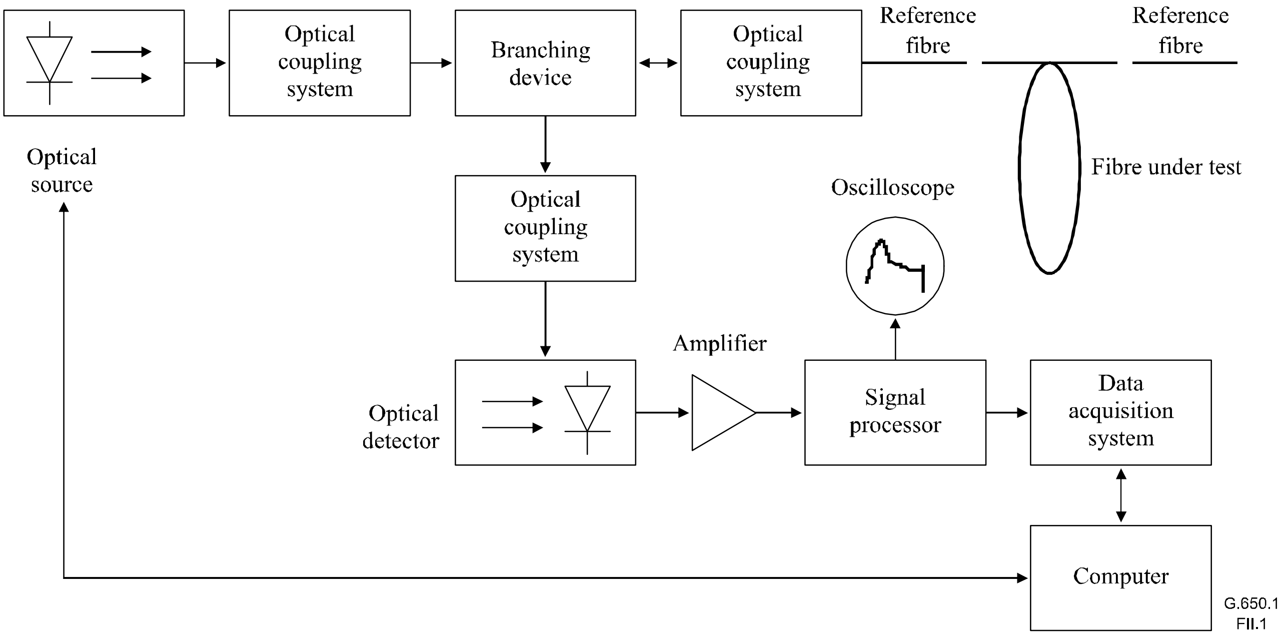


Figure II.1 – Schematic of apparatus for chromatic dispersion uniformity measurement

II.2.2 **Optical source** (as in clause 5.4.2.2.2)

II.2.3 **Optical coupling system** (as in clause 5.4.2.2.3)

II.2.4 **Branching device** (as in clause 5.4.2.2.4)

II.2.5 **Optical detector** (as in clause 5.4.2.2.5)

II.2.6 **Amplifier** (as in clause 5.4.2.2.6)

II.2.7 **Signal processor** (as in clause 5.4.2.2.7)

II.2.8 **Cladding mode stripper** (as in clause 5.4.2.2.8)

II.2.9 Reference fibre

The refractive index profile of the reference fibre shall be similar to that of the test fibre and its length is restricted to maintain a good longitudinal uniformity, but it shall be longer than the input dead-zone of the backscattering measurements. In addition, the mode field diameter of the reference fibre shall be measured as a function of wavelength. This reference fibre can be used to estimate the absolute value of the mode field diameter and relative index difference from the backscattering measurements.

II.3 Measurement procedure

a) Connect reference fibres to both ends of the test fibre.

b) Align the fibre under test with the optical coupling system.

c) As b) in clause 5.4.2.3.

d) As c) in clause 5.4.2.3.

e) Obtain the bidirectional backscattering imperfection loss curve using the two measured and recorded unidirectional backscattering loss curves, according to the procedure outlined in the following:

Let $S_1(x)$ and $S_2(z)$ be functions describing the two unidirectional backscattering loss curves expressed in dB, with x and z being the distances from the fibre ends nearest the respective launch sites and $L = x + z$. The bidirectional backscattering imperfection loss curve is given by:

$$I(x,z) = \frac{S_1(x,\lambda) + S_2(L-x,\lambda)}{2} \tag{II-1}$$

f) Obtain the imperfection loss normalized by that at position x_0 in the reference fibre according to the procedure outlined in the following:

$$I_n(x,\lambda) = I(x,\lambda) - I(x_0,\lambda)$$

$$= 20\log\left\{\frac{W(x_0,\lambda)}{W(x,\lambda)}\right\} + 10\log\left[\left\{\frac{1+0.62\Delta(x)}{1+0.62\Delta(x_0)}\right\}\left\{\frac{50-\Delta(x)}{50-\Delta(x_0)}\right\}\right]$$

$$= 20\ \log\left\{\frac{W(x_0,\lambda)}{W(x,\lambda)}\right\} + k \tag{II-2}$$

where coefficient k is defined as:

$$k = 10\log\left[\left\{\frac{1+0.62\Delta(x)}{1+0.62\Delta(x_0)}\right\}\left\{\frac{50-\Delta(x)}{50-\Delta(x_0)}\right\}\right] \tag{II-3}$$

g) Obtain the mode field diameter distribution $2W(x, \lambda)$ according to the procedure outlined in the following:

Let the mode field diameter at position x_0 in the reference fibre be $2W(x_0, \lambda)$. The mode field diameter distribution is given by:

$$2W(x,\lambda) = 2W(x_0,\lambda)\cdot 10^{\frac{-I_n(x,\lambda)+k}{20}} \quad \text{(II-4)}$$

If the reference and test fibres have the same index profile and relative index difference, let coefficient $k = 0$.

If the relative index difference in the test fibre is not the same as that in the reference fibre, determine coefficient k by using Equation II-3 and the mode field diameter value at x in the test fibre which is evaluated in advance.

If the adjustment factors f and g, which are determined as described in c) in clause 5.1.4.3.2, are given, the mode field diameter distribution is given by:

$$2W(x,\lambda) = 2W(x_0,\lambda)\cdot 10^{\frac{-g\cdot I_n(x,\lambda)+f}{20}} \quad \text{(II-5)}$$

If the relative index difference in the test fibre is unknown, the mode field diameter value at x in the test fibre is obtained with Equation II-6 considering the second position x_1 in the reference fibre.

$$2W(x,\lambda) = 2W(x_0,\lambda)\cdot \left[\frac{2W(x_1,\lambda)}{2W(x_0,\lambda)}\right]^{\frac{I(x,\lambda)-I(x_0,\lambda)}{I(x_1,\lambda)-I(x_0,\lambda)}} \quad \text{(II-6)}$$

h) Repeat the above procedures for two or more different wavelengths.

i) Obtain the coefficients g_0, g_1, and g_2 which satisfy Equation II-7 using the above mode field radii $W(x, \lambda)$:

$$W(x,\lambda) = g_0(x) + g_1(x)\lambda^{1.5} + g_2(x)\lambda^6 \text{ (three or more wavelengths)} \quad \text{(II-7)}$$

or:

$$W(x,\lambda) = g_0(x) + g_1(x)\lambda^{1.5} \text{ (two or more wavelengths)} \quad \text{(II-8)}$$

This expression may be evaluated by a least squares fit of the data $W(x, \lambda_i)$ ($i = 1, ..., n$).

j) Obtain the waveguide dispersion distribution $D_w(x, \lambda)$ in ps/(nm × km) outlined in the following:

$$D_w(x,\lambda) = \frac{\lambda}{2\pi^2 cnW(x,\lambda)^2}\left\{1 - \frac{2\lambda}{W(x,\lambda)}\left(\frac{3}{2}g_1(x)\lambda^{0.5} + 6g_2(x)\lambda^5\right)\right\}$$

(three or more wavelengths) (II-9)

or:

$$D_w(x,\lambda) = \frac{\lambda}{2\pi^2 cnW(x,\lambda)^2}\left\{1 - \frac{3g_1(x)\lambda^{1.5}}{W(x,\lambda)}\right\} \text{ (two or more wavelengths)} \quad \text{(II-10)}$$

where c and n show the light velocity in m/s and the maximum refractive index of the core, respectively.

k) Obtain the relative index difference distribution $\Delta(x)$ in % according to the procedure outlined in the following:

If the reference and test fibres have the same index profile, obtain the coefficients c_0, c_1 and c_2 at the reference fibre which satisfy the following equation using mode field diameter $2W(x_0, \lambda)$, core diameter $2a(x_0)$ and cut-off wavelength $\lambda_c(x_0)$:

$$\frac{W(x_0,\lambda)}{a(x_0)} = c_0 + c_1\left\{\frac{\lambda}{\lambda_c(x_0)}\right\}^{1.5} + c_2\left\{\frac{\lambda}{\lambda_c(x_0)}\right\}^{6} \qquad \text{(II-11)}$$

Calculate the characteristic of the ratio R_W of mode field diameters of two wavelengths (λ_1 and λ_2) as a function of the cut-off wavelength λ_c using the above coefficients c_0, c_1 and c_2.

$$R_W \equiv \frac{2W(\lambda_1)}{2W(\lambda_2)} = \frac{c_0 + c_1\left(\frac{\lambda_1}{\lambda_c}\right)^{1.5} + c_2\left(\frac{\lambda_1}{\lambda_c}\right)^{6}}{c_0 + c_1\left(\frac{\lambda_2}{\lambda_c}\right)^{1.5} + c_2\left(\frac{\lambda_2}{\lambda_c}\right)^{6}} \qquad \text{(II-12)}$$

Determine the approximate function between the ratio R_W of mode field diameters at two wavelengths and cut-off wavelength λ_c.

Obtain the cut-off wavelength distribution $\lambda_c(x)$ by applying the above approximate function to the ratio of the measured mode field diameter distributions.

Obtain the core diameter distribution $2a(x)$ substituting the mode field diameter distribution $2W(x)$ and the cut-off wavelength distribution $\lambda_c(x)$ into Equation II-11.

Obtain the relative index difference distribution $D(x)$ in % using Equation II-13:

$$\Delta(x) = \left\{\frac{a(x_0)}{a(x)}\right\}^2 \left\{\frac{\lambda_c(x)}{\lambda_c(x_0)}\right\}^2 \Delta(x_0) \qquad \text{(II-13)}$$

Alternatively, relative index difference $\Delta(x)$ in % is obtained with Equation II-14 using the relative index difference at position x_0 in the reference fibre $\Delta(x_0)$.

$$\Delta(x) = \frac{1}{0.62}\left[\{1 + 0.62\Delta(x_0)\}\cdot 10^{\frac{I_n(x,\lambda) - 20\log\left\{\frac{2W(x_0,\lambda)}{2W(x,\lambda)}\right\}}{10}} - 1\right] \qquad \text{(II-14)}$$

l) Obtain the material dispersion distribution $D_m(x, \lambda)$ in ps/(nm × km) using the above relative index difference distribution $\Delta(x)$.

Here, the approximate equation of the material dispersion can be obtained as a function of wavelength and relative index difference.

The material dispersion $D_m(\lambda)$ can be estimated by using Equations II-15 and II-16:

$$D_m(\lambda) = -\frac{\lambda}{c}\frac{d^2 n(\lambda)}{d\lambda^2} \qquad \text{(II-15)}$$

$$n^2(\lambda) - 1 = \sum_{i=1}^{k} \frac{B_i \lambda^2}{\lambda^2 - A_i^2} \qquad \text{(II-16)}$$

where A_i and B_i show the Sellmeier coefficients and both coefficients A_i and B_i as a function of dopant content corresponding to the relative-index difference D were given in [b-Kobayashi] and [b-Fleming].

Calculate an estimated function $D_m(\lambda)$ of material dispersion against the relative-index difference D by using Equations II-15 and II-16.

The material dispersion against the relative-index difference D is obtained as follows:

$$D_m(\lambda) = m_1(\lambda) + h \cdot \Delta \cdot m_2(\lambda) \qquad \text{(II-17)}$$

where h shows the constant.

Obtain the chromatic dispersion distribution $D(x,\lambda)$ in ps/nm × km outlined in the following:

$$D(x,\lambda) = D_m(x,\lambda) + D_w(x,\lambda) \qquad \text{(II-18)}$$

II.4 Presentation of the results

a) Test set-up arrangement.

b) Kind of signal processing used.

c) Pulse width.

d) Test wavelengths.

e) Mode field diameter distribution in mm.

f) Chromatic dispersion distribution in ps/nm × km.

Appendix III

Example of a matrix model

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

The following is an example of an $m \times n = 38 \times 3$ matrix, as described in clause 5.4.4.3, for ITU-T G.652 fibres. Please note it is given for illustrative purposes only. If the spectral attenuation is to be estimated over the range of 1240 nm to 1600 nm (in steps of 10 nm) using 1310 nm, 1380 nm, and 1550 nm as predictor wavelengths, an example of matrix elements which has been shown to be applicable [b-Hanson] for some ITU-T G.652 fibres follows:

Output wavelength (μm)	**Predictive wavelengths**		
	1310 nm	**1380 nm**	**1550 nm**
1.23	1.46027	–0.04235	–0.20771
1.24	1.35288	–0.01493	–0.13289
1.25	1.31704	–0.00412	–0.14768
1.26	1.26613	–0.00997	–0.13715
1.27	1.20167	–0.00843	–0.10635
1.28	1.14970	–0.01281	–0.06363
1.29	1.11290	–0.01059	–0.06245
1.30	1.03600	–0.00711	0.00711
1.31	0.96276	0.00342	0.05412
1.32	0.90437	0.01435	0.08572
1.33	0.86168	0.02098	0.11776
1.34	0.83194	0.05500	0.05849
1.35	0.73415	0.08336	0.14196
1.36	0.83266	0.11032	–0.10694
1.37	0.69137	0.22596	–0.05961
1.38	0.01006	0.99798	–0.01126
1.39	–0.25502	0.94764	0.48887
1.40	0.00227	0.58463	0.51813
1.41	0.25780	0.33834	0.40811
1.42	0.29085	0.20419	0.49620
1.43	0.29329	0.13569	0.54995
1.44	0.33133	0.09266	0.51936
1.45	0.31608	0.06343	0.55905
1.46	0.24183	0.04483	0.68361
1.47	0.29207	0.03019	0.59222
1.48	0.19214	0.02196	0.75669

Output wavelength (μm)	Predictive wavelengths		
	1310 nm	1380 nm	1550 nm
1.49	0.18650	0.01132	0.76122
1.50	0.21242	0.00541	0.70722
1.51	0.16884	0.00648	0.75347
1.52	0.11484	–0.00091	0.84972
1.53	0.09334	0.00419	0.85304
1.54	0.07231	–0.00021	0.88512
1.55	0.03111	–0.00115	0.94957
1.56	0.07054	–0.00321	0.87414
1.57	–0.03723	–0.01127	1.08140
1.58	–0.02543	0.00556	1.01041
1.59	–0.01370	0.00457	0.99389
1.60	–0.06916	–0.00107	1.11623

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