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INTERNATIONAL STANDARD

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Optical fibres –
Part 1-44: Measurement methods and test procedures – Cut-off wavelength

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OPTICAL FIBRES –

Part 1-44: Measurement methods and test procedures – Cut-off wavelength

FOREWORD

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IEC 60793-1-44 has been prepared by subcommittee 86A: Fibres and cables, of IEC technical committee 86: Fibre optics. It is an International Standard.

This third edition cancels and replaces the second edition published in 2011. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) used the diameter of the fibre loops to describe deployment;
b) added Annex D related to cut-off curve artifacts;
c) reorganized information and added more figures to clarify concepts.

The text of this International Standard is based on the following documents:

Draft	Report on voting
86A/2314/FDIS	86A/2327/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

This document is to be read in conjunction with IEC 60793-1-1.

A list of all parts of the IEC 60793-1 series, published under the general title *Optical fibres – Measurement methods and test procedures*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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OPTICAL FIBRES –

Part 1-44: Measurement methods and test procedures – Cut-off wavelength

1 Scope

This part of IEC 60793 establishes uniform requirements for measuring the cut-off wavelength of single-mode optical fibre, thereby assisting in the inspection of fibres and cables for commercial purposes.

This document gives methods for measuring the cut-off wavelength for uncabled or cabled single mode telecom fibre. These procedures apply to all category B and C fibre types.

There are three methods of deployment for measuring the cut-off wavelength:

- method A: cable cut-off using uncabled fibre 22 m long sample, λ_{cc};
- method B: cable cut-off using cabled fibre 22 m long sample, λ_{cc};
- method C: fibre cut-off using uncabled fibre 2 m long sample, λ_{c}.

All methods require a reference measurement. There are two reference-scan techniques, either or both of which can be used with all methods:

- bend-reference technique;
- multimode-reference technique using category A1(OM1-OM5) multimode fibre.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60793-1-1, *Optical fibres – Part 1-1: Measurement methods and test procedures – General and* guidance

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

4 Background

Theoretical cut-off wavelength is the shortest wavelength at which only the fundamental mode can propagate in a single-mode fibre, as computed from the refractive index profile of the fibre.

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. For purposes of determining fibre performance in a telecommunications network, theoretical cut-off wavelength is less useful than the lower value actually measured when the fibre is deployed.

Measured cut-off wavelength is defined as the wavelength greater than which the ratio 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 at the cut-off wavelength.

Because measured cut-off wavelength depends on the length and bends of the fibre, the resulting value of cut-off wavelength depends on whether the measured fibre is configured in a deployed, cabled condition or if it is short and uncabled. Consequently, there are two overall types of cut-off wavelength:

- cable cut-off wavelength (λ_{cc}) measured in an uncabled fibre deployment condition (method A), or in a cabled condition (method B);
- fibre cut-off wavelength (λ_c) measured on a short length of uncabled, primary-coated fibre (method C).

Cable cut-off wavelength is the preferred attribute to be specified and measured.

5 Overview of methods

All of the methods shall use the transmitted-power technique. A general system block diagram is depicted in Figure 1. A fibre specimen is scanned by a wavelength spectrum. The output optical power is measured and stored. This stored data is then analysed against a reference power spectrum. The reference scan normalizes any wavelength-dependent fluctuations in the measurement equipment that is not associated with the loss of the LP_{11} mode. The resulting attenuation will thus properly characterize the cut-off wavelength.

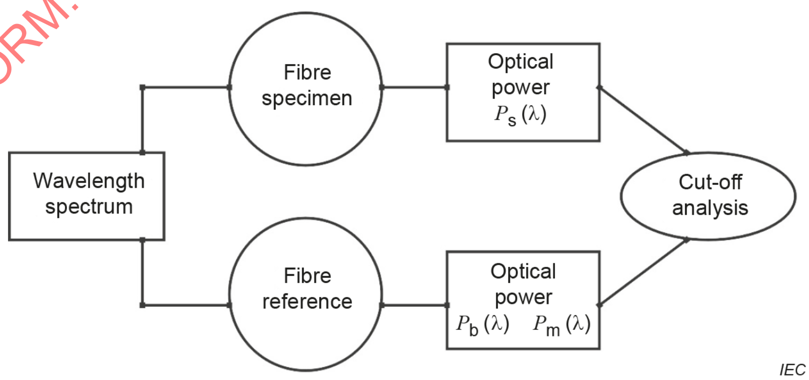

Figure 1 – Cut-off measurement system block diagram

The reference scan uses one of the following two techniques:

- bend reference where a small diameter bend is added to the fibre specimen;
- multimode reference where the optical power through an A1(OM1-OM5) fibre is measured.

Either reference technique can determine the cut-off wavelength of a fibre specimen in a cabled or uncabled condition.

The fibre cut-off wavelength, λ_c, measured under the standard length and bend conditions described in this document, will generally exhibit a value larger than the cable cut-off wavelength, λ_{cc}. For normal installed cable spans, it is common for the measured λ_c value to exceed the long fibre's transmission wavelength.

Cable cut-off wavelength is more useful in describing an installed network system performance and capability, while fibre cut-off would apply to short cables or pigtails. The two cut-off wavelengths can be mapped to each other for a specific fibre type and cut-off measurement method. The customer and the supplier shall agree to the confidence level of each mapping function established (see Clause 11 for details).

6 Reference test method

Method A, cable cut-off wavelength using uncabled fibre, is the reference test method (RTM). This method shall be used to settle any disputes.

7 Apparatus

7.1 Light source

Provide a filtered white light source, with line width not greater than 10 nm, stable in position and intensity. The light source should be capable of operating over the wavelength range 1 000 nm to 1 600 nm for most category B fibres. An operating range of 800 nm to 1 700 nm may be necessary for some B-655 fibres, B-656 fibres or category C fibres. A scanning monochromator with a halogen bulb is one example of this kind of source.

7.2 Modulation

Modulate the light source to prevent ambient light affecting the results, and to aid signal recovery. A mechanical chopper with a reference output is a suitable arrangement.

7.3 Launch optics

Provide launch optics, such as a lens system or a multimode fibre, to overfill the test fibre over the full range of measurement wavelengths. This launch is relatively insensitive to the input end face position of the single-mode fibre and is able to excite the fundamental and any higher-order modes in the specimen. If using a butt splice, provide means of avoiding interference effects.

When using a multimode fibre, overfilling the reference fibre can produce an undesired ripple effect in the power-transmission spectrum. Restrict the launch sufficiently to eliminate the ripple effect. One example of restricted launch is in method A, attenuation by cut-back, of IEC 60793-1-40. Another example of restricted launch is a mandrel-wrap mode filter with sufficient (approximately 4 dB) insertion loss.

7.4 Support and positioning apparatus

Provide a means to stably support the input and output ends of the specimen for the duration of the test; vacuum chucks, magnetic chucks, or connectors may be used for this purpose. Support the fibre ends such that they can be repeatedly positioned in the launch and detection optics. When measuring λ_{cc} in method B, provide a means to suitably support the cable ends. The mechanism used to hold the fibre ends allows for fibre positioning with respect to the launch and detection optics. Holding and moving of the fibre should not cause micro-bends that affect the measurement accuracy.

7.5 Deployment mandrel

7.5.1 General

The fibre specimen's two ends, input and output, are mechanically held in place during the measurement. The deployment and length of the specimen, together with the support apparatus, are key elements of the measurement method, and they distinguish the types of cut-off wavelength.

Additional, alternative deployments may be used if the results obtained have been demonstrated to be empirically equivalent to the results obtained using the standard deployment, to within 10 nm, or they are greater than those achieved with the standard configurations.

7.5.2 Cable cut-off wavelength deployment, method A

Provide a means to make an 80 mm diameter loop at each end of the specimen and a loop of diameter ≥ 280 mm in the central portion. See Figure 2.

Dimensions in millimetres

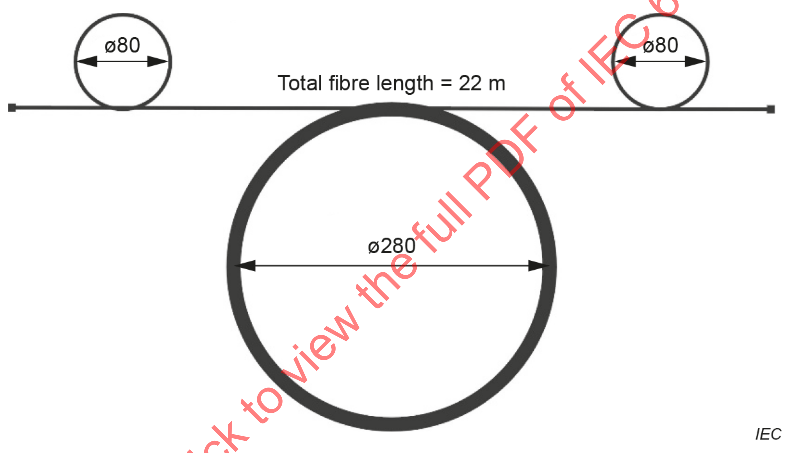

Figure 2 – Deployment configuration for cable cut-off wavelength λ_{cc}, method A

7.5.3 Cable cut-off wavelength deployment, method B

Provide a means to make an 80 mm diameter loop at each end of the specimen. See Figure 3. The cabled fibre between the two 80 mm loops has a bending diameter greater than 280 mm.

Dimensions in millimetres

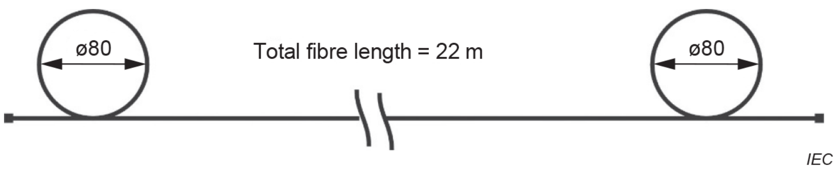

Figure 3 – Deployment configuration for cable cut-off wavelength λ_{cc}, method B

7.5.4 Fibre cut-off wavelength deployment, method C

Provide means to route a fibre specimen through one complete circular loop having a diameter equal to 280 mm, see Figure 4.

Dimensions in millimetres

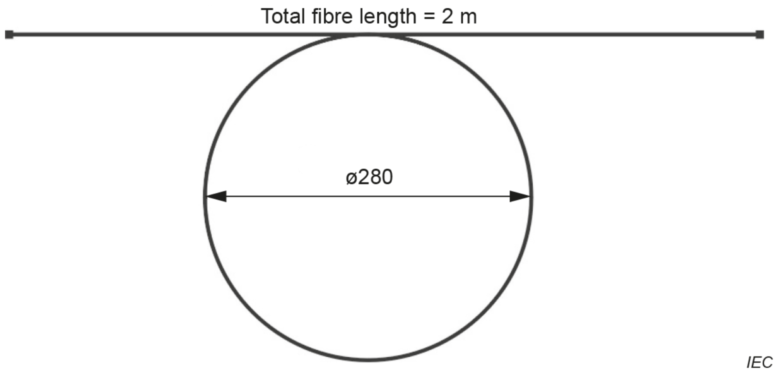

Figure 4 – Standard deployment for fibre cut-off wavelength measurement

7.6 Detection optics

Couple all power emitted from the specimen onto the active region of the detector. As examples, an optical lens system, a butt splice with a multimode fibre pigtailed to a detector, or direct coupling may be used.

7.7 Detector assembly and signal detection electronics

Use a detector that is sensitive to the output radiation over the range of wavelengths to be measured and that is linear over the range of intensities encountered. A typical system might include a germanium or InGaAs photodiode, operating in the photo-voltaic mode, and a current-sensitive preamplifier, with synchronous detection by a lock-in amplifier. Generally, a computer is required to analyse the data.

7.8 Cladding mode stripper

Provide a means to remove cladding-mode power from the specimen. Under some circumstances, the fibre coating will perform this function; otherwise, provide methods or devices that extract cladding-mode power at the input and output ends of the specimen.

8 Sampling specimen

8.1 Specimen length

Choose the specimen length according to which parameter is being measured and, if the parameter is cable cut-off wavelength, the method to be used. See the appropriate annex: Annex A or Annex B for the cable cut-off wavelength measurement or Annex C for fibre cut-off wavelength.

8.2 Specimen end face

Prepare a flat end face, orthogonal to the fibre axis, at the input and output ends of each specimen. An optical fibre cleaver is often used to achieve very flat and clean end faces.

9 Procedure

9.1 Positioning of specimen in apparatus

9.1.1 General requirements for all methods

Align the input and output ends of the specimen to the launch and detection optics. Do not change the launch and detection conditions during the course of the measurement.

Unless otherwise specified, when installing the specimen in the apparatus, and when using a cladding-mode stripper, avoid imposing any additional fibre bends smaller than those specified in the configuration for the particular measurement being made.

9.1.2 Deployment requirements for each method

Deploy the specimen using the information in Clause 7 and the following annexes:

- cable cut-off wavelength, method A (see Annex A);
- cable cut-off wavelength, method B (see Annex B);
- fibre cut-off wavelength, method C (see Annex C).

9.2 Measurement of output power

9.2.1 Overview

Record the output power, $P_s(\lambda)$, along the wavelength range, in increments of 10 nm or less. The range shall be broad enough to encompass the expected cut-off wavelength. The measured power is then normalized by the reference power producing curves similar to Figure 5, bend reference and Figure 6 multimode reference.

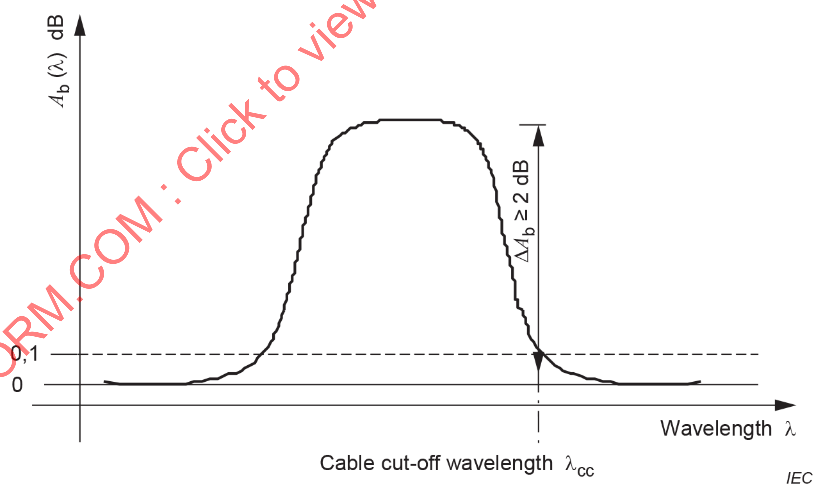

Figure 5 – Cut-off wavelength using the bend-reference technique

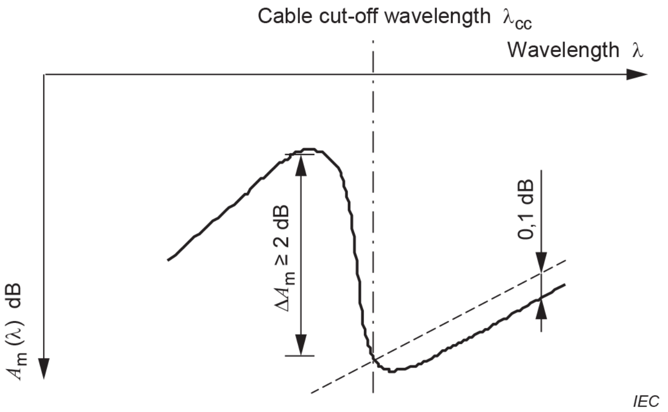

Figure 6 – Cut-off wavelength using the multimode-reference technique

9.2.2 Bend-reference technique

With input and output conditions unchanged, introduce a smaller-diameter bend between input and the output. Record the transmitted spectral power, $P_b(\lambda)$, over the same wavelength range and with the same spectral increments as in making the original measurement on the specimen.

The exact value of the smaller diameter may be determined prior to measurement; it should be small enough to attenuate the second-order mode, but not too small in order to avoid macrobending effects at higher wavelengths. A diameter between 20 mm and 60 mm is typical for most B652 to B656 fibres.

For some bend insensitive fibres (category B-657), the diameter may need to be smaller, and this measurement technique may not be adequate for these fibres. Curve artifacts can persist and require the use of both techniques described in Annex D.

9.2.3 Multimode-reference technique

Replace the specimen with a short (< 10 m) length of category A1(OM1-OM5) multimode fibre as a reference. Record the transmitted signal power, $P_m(\lambda)$, over the same wavelength range and with the same spectral increments as in making the original measurement on the specimen.

NOTE Ripples can occur in the reference spectrum $P_m(\lambda)$. Provide a means to add mode mixing which can reduce this effect; this can be done by wrapping a multimode fibre at least 5 times around a mandrel 10 mm to 20 mm in diameter. A1(OM2-OM5) type multimode fibres are preferred for this technique.

10 Calculations

10.1 Bend-reference technique

Calculate the spectral transmittance of the specimen without the small diameter bend, referenced to the condition where the smaller-radius bend is introduced:

$$A_b(\lambda) = 10\log_{10}\frac{P_s(\lambda)}{P_b(\lambda)} \text{ in dB} \quad (1)$$

where

$A_b(\lambda)$ is the spectral transmittance referenced to the small diameter bend (dB);

$P_s(\lambda)$ is the spectral optical power through the fibre specimen;

$P_b(\lambda)$ is the spectral optical power through the sample with small diameter bend.

Figure 5 shows a schematic result. The short and long wavelength edges are determined by the specimen deployed with and without the smaller-radius bend, respectively. Determine the longest wavelength at which $A_b(\lambda)$ = 0,1 dB from Figure 5. This is the cut-off wavelength, provided that ΔA_b is equal to or greater than 2 dB.

If ΔA_b < 2 dB, or if it is unobservable, broaden the wavelength scan and enlarge the single-mode launch conditions, or decrease the smaller-bend radius. Repeat these adjustments and the measurement procedure until ΔA_b > 2 dB.

For certain implementations of bend-insensitive fibres (category B-657), ΔA_b will not reach 2 dB loss, because of the very nature of these fibres. It is recommended to use the multimode-reference technique as reference scan for these fibres. See Annex D for dealing with curve artifacts that can affect the results.

10.2 Multimode-reference technique

Calculate the spectral transmittance of the specimen, referenced to that of the multimode fibre:

$$A_m(\lambda) = 10\log_{10}\frac{P_s(\lambda)}{P_m(\lambda)} \tag{2}$$

where

$A_m(\lambda)$ is the spectral transmittance referenced to the multimode fibre (dB);

$P_s(\lambda)$ is the spectral optical power through the specimen;

$P_m(\lambda)$ is the spectral optical power through the multimode reference fibre.

Figure 6 shows a schematic result.

Fit a straight line to the long-wavelength portion of $A_m(\lambda)$, displacing it upward by 0,1 dB, as shown by the dashed line in Figure 6. Determine the longest wavelength at which this displaced line intersects with $A_m(\lambda)$. This is the cut-off wavelength, provided that ΔA_m is equal to or greater than 2 dB. Between measured data points, $A_m(\lambda)$ is defined by linear interpolation.

If ΔA_m < 2 dB, or if it is unobservable, broaden the wavelength scan and enlarge the single-mode launch conditions. Repeat these adjustments and the measurement procedure until ΔA_m > 2 dB, and until the long-wavelength tail is of adequate length to be fitted by a straight line.

NOTE When using the multimode-reference technique, fibres with high cut-off wavelengths, when combined with reference fibres with high water peaks, can have erroneous values reported as cut-off wavelength.

For certain implementations of bend-insensitive fibres (category B-657), the bend-reference technique is not the optimal technique as reference scan. For these fibres, the multimode-reference technique is recommended. See Annex D for dealing with curve artifacts that can affect the results.

11 Mapping functions

A mapping function is a formula by which the measured results of one type of cut-off wavelength are used to predict the results that one would obtain from another type. Figure 7 illustrates the cut-off wavelength difference between the fibre cut-off method C and the cable cut-off method A for a specific fibre type.

An empirical mapping function is specific to a particular fibre type and method. Generate mapping functions by doing an experiment in which a variety of fibre specimens between the two fibre deployment methods are sampled. A linear regression of the respective values will often produce a satisfactory mapping function. When establishing criteria for fibre selection, residual errors in the regression shall be taken into account.

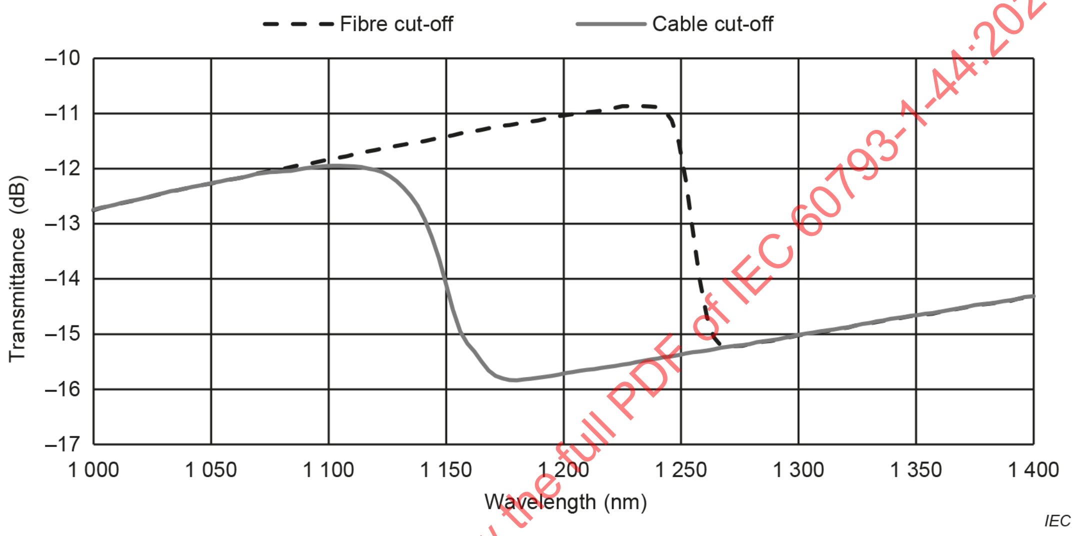

Figure 7 – Cable cut-off vs fibre cut-off for a specific fibre (multimode reference)

12 Results

12.1 Report the following information with each measurement:

- date and title of measurement;
- identification of specimen;
- measurement results.

12.2 The following information shall be available upon request:

- if measuring cable cut-off wavelength, the method used: A or B;
- length of specimen;
- reference technique used (bend or multimode);
- type of multimode fibre used (if using multimode-reference technique);
- description of all key equipment used: light source, launch optics, cladding-mode stripper, specimen-support mechanisms, and detection optics;
- description of monochromator (spectral scanning range, spectral width, and incremental steps);
- description of detection and recording techniques;
- description of deployment configuration used;

- typical plot of the spectral curve, $A_b(\lambda)$ or $A_m(\lambda)$;
- date and certificate of latest calibration of measurement equipment.

13 Specification information

The detail specification shall specify the following information:

- type of fibre or cable to be measured;
- failure or acceptance criteria;
- information to be reported;
- any deviations to the procedure that apply.

Annex A
(normative)

Requirements specific to method A – Cable cut-off wavelength, λ_{cc}, using uncabled fibre

A.1 Specimen length

Use a 22 m ± 1 m total length of (uncabled) optical fibre.

A.2 Procedure – Position specimen on deployment mandrel

In order to conservatively simulate cabling effects, the specimen has a central coil 20 m long with a minimum diameter of 280 mm (see Figure 2). The 20 m fibre coil has a minimum diameter of 280 mm and should be loosely coiled with minimal stress. The remaining fibre is used to create two 1 m long ends. This specimen is then placed in front of the measurement instrument where an 80 mm diameter loop is applied to each end. The 80 mm loops simulate the effects of a splice organizer. Figure A.1 shows an alternative deployment method for cable cut-off. Alternative to placing loop at each end, two 80 mm loops can be place at one end.

Since λ_{cc} represents a maximum cut-off value, this configuration is sufficient to ensure specification compliance, because any further effects of cabling, installation, and deployment can only reduce further the cable cut-off wavelength value.

Dimensions in millimetres

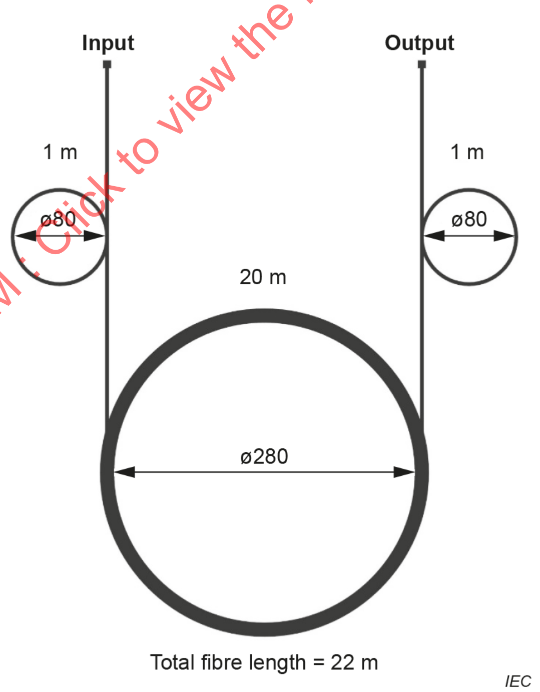

Figure A.1 – Alternative cable cut-off deployment

Annex B
(normative)

Requirements specific to method B – Cable cut-off wavelength, λ_{cc}, using cabled fibre

B.1 Specimen length

Use a 22 m ± 1 m total length of optical cable, with a 1 m length of decabled fibre at each end.

B.2 Procedure – Position specimen on deployment mandrel

Expose 1 m of cabled fibre from each end, and deploy the specimen as shown in Figure 3. The middle 20 m of the jacketed cable shall be substantially straight having any bend greater than 280 mm so that the deployment does not have a significant effect on the subsequent measurement results. To simulate the effects of splice organizers, apply one loop of 80 mm diameter to each 1 m end of the decabled fibre length or two loops of 80 mm diameter to one end of the decabled fibre. The cabled ends should be secured as to not move during measurement.

NOTE For short cables, for example a pigtail with a length shorter (and possibly a bending radius larger) than described in this method, it is possible the cable introduces modal noise near the cut-off wavelength when lossy splices are present (> 0,5 dB).

Annex C
(normative)

Requirements specific to method C – Fibre cut-off wavelength, λ_c

C.1 Specimen length

Use an optical fibre with a total length of 2 m ± 0,2 m.

C.2 Procedure – Position specimen on deployment mandrel

Bend the specimen into a loosely constrained circular loop having a diameter of 280 mm (see Figure 4).

Alternatively, the loop placed in the fibre may consist of two arcs (each of 180°) of 280 mm diameter connected by tangents. This set-up is shown in Figure C.1, where the lower semi-circular mandrel is allowed to move to take up any slack fibre without requiring the movement of any of the optics, or placing any significant tension on the rest of the fibre specimen. The remaining fibre shall be substantially free of external stresses.

Dimensions in millimetres

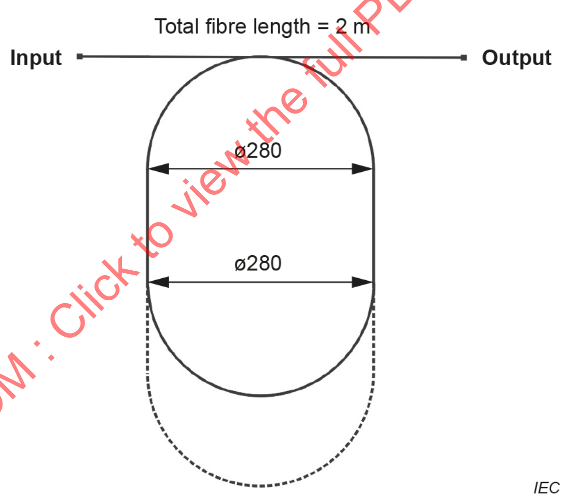

Figure C.1 – Alternative fibre cut-off deployment – Sliding semi-circle

There are a variety of alternative deployments; Figure C.2 and Figure C.3 depict other variations. Alternative deployments may have larger bends greater than 280 mm as long as they do not significantly affect the measurement result. Alternate deployment methods are compared to the deviation from the standard method and should not exceed 10 nm. When evaluating the deviation accuracy, one should also measure the deviation of deployment, meaning the variation of the measurement when the same fibre is redeployed.

Dimensions in millimetres

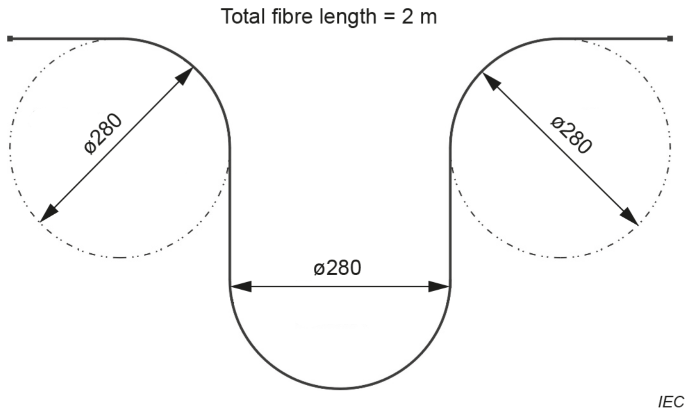

Figure C.2 – Alternative fibre cut-off deployment – Multi-bend

Dimensions in millimetres

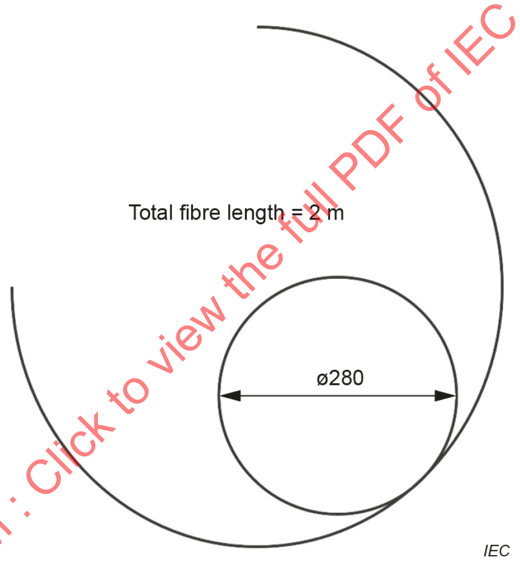

Figure C.3 – Alternative fibre cut-off deployment – Large curve

Annex D
(informative)

Cut-off curve artifacts

D.1 Description of curve artifacts

Sometimes, the transition between LP_{11} to LP_{01} is not smooth. Curve artifacts can appear as small humps located around the transition area. The origin of these humps is related to modes that are not associated with the axial modes propagating in the core/cladding wave guide. These curve humps can produce errors when using standard measurement practices. Figure D.1 shows a cut-off curve where a modal hump is large enough to trigger the 0,1 dB threshold of the linear fit resulting in a cut-off wavelength calculation that is too large.

To reduce the effects of these modal humps, two methods have been proposed:

- applying advance numerical curve fitting techniques that filter the humps;
- slightly modifying the fibre deployment to attenuate the modes.

For both techniques, the standard cut-off curve measurements should serve as a guide in evaluating the accuracy of the method.

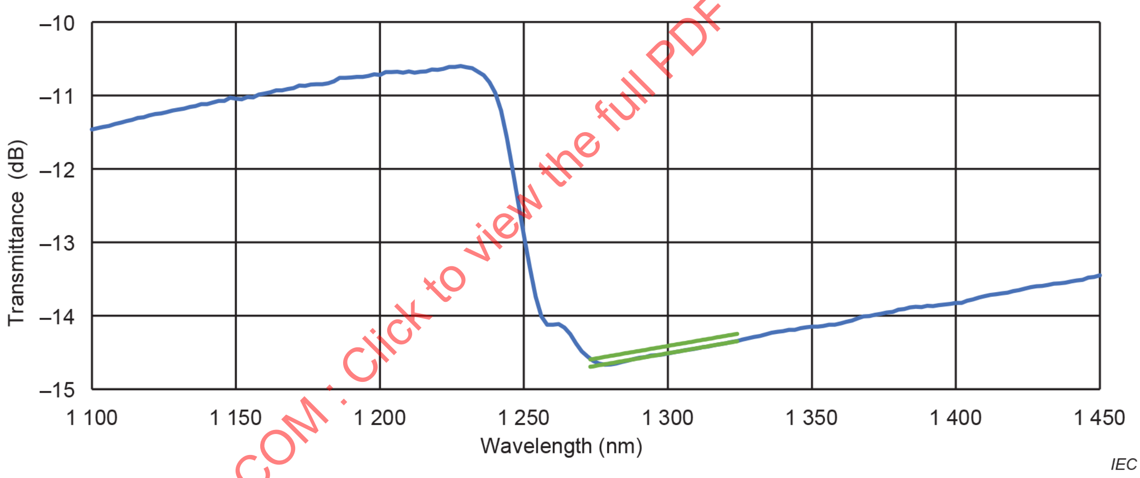

Figure D.1 – Cut-off curve with linear fit error (multimode reference)

D.2 Curve-fitting technique for artifact filtering

D.2.1 Overview

The general concept is to fit two curves to the spectral transmittance and use their intersection to define the cut-off wavelength. Figure D.2 shows a curve fitting result that filters a hump measured by a fibre cut-off multimode reference method. When using curve fitting, one shall observe the fit overlay on the cut-off curve to ensure that the fit was properly applied. Sometimes the curve fit can be influenced by the location of the humps and provide results that do not represent the loss of the LP_{11} mode.

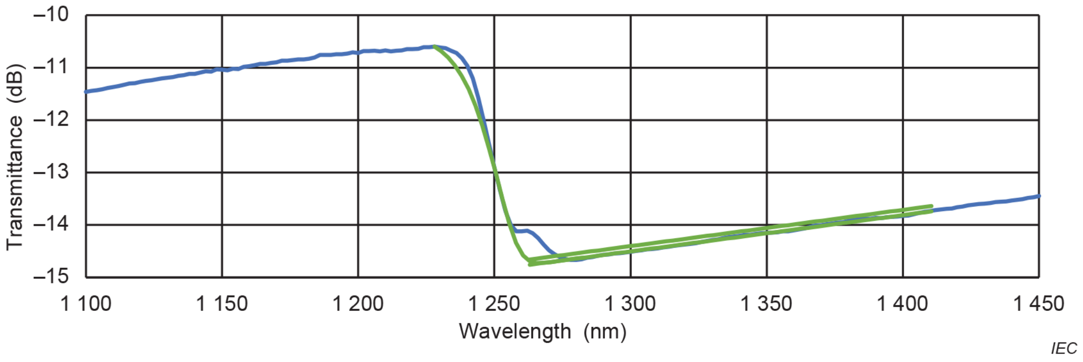

Figure D.2 – Fibre cut-off curve fitting technique (multimode reference)

D.2.2 General

If curve fitting is considered necessary for improving precision, then one method is described below. The method describes a seven step process for smoothing data through numerical filtering. The steps 1 to 3 define the LP_{01} region, or upper-wavelength region. Steps 4 to 5 define the transition region, where LP_{11} attenuation begins to increase. Step 6 characterizes this region according to a theoretical model. Step 7 computes the cut-off wavelength from the characterization parameters.

This analysis is applicable for λ_c and λ_{cc} measured using either the bend-reference technique or the multimode-reference technique. The term $A(\lambda)$ represents either spectral transmittance $A_b(\lambda)$ or $A_m(\lambda)$. Figure D.3 illustrates the regions location and the curve fit applied to each of them.

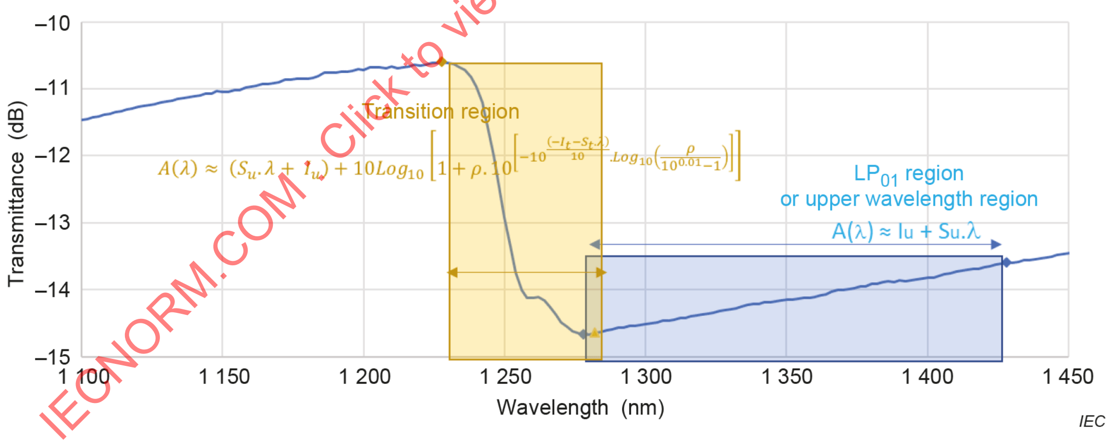

Figure D.3 – Curve fitting regions

D.2.3 Step 1: define the upper wavelength region

The upper wavelength region starts at a wavelength ("start wavelength", λ^{u}_{start}) and ends at a higher wavelength ("end wavelength", λ^{u}_{end}).

- Start wavelength
  1) Bend reference technique

     One method is to find the wavelength at which the spectral transmittance is maximum.

     For wavelengths greater than this wavelength, the start wavelength is the wavelength at which the function $A(\lambda) - 8 + 8\lambda$, with λ in µm, is minimum.
  2) Multimode reference technique

     One method is to find the wavelength at which the function $A(\lambda) - A(\lambda + 10 \text{ nm})$ is maximum.

     For wavelengths greater than this wavelength, the start wavelength is the wavelength at which $A(\lambda)$ is minimum.
- End wavelength

  The end wavelength, λ^{u}_{end}, is the start wavelength, λ^{u}_{start}, plus 150 nm.

D.2.4 Step 2: characterize the spectral transmittance

Characterize the spectral transmittance, $A(\lambda)$, of the upper wavelength region as a linear equation in wavelength, λ:

$$A(\lambda) \approx I_u + S_u \cdot \lambda \quad \text{(D.1)}$$

where

$A(\lambda)$ is the spectral transmittance;

I_u and S_u are the intercept and the slope of the linear equation respecting the description below.

a) Using the bend-reference technique

   Set I_u to the median transmittance value of the upper wavelength region.

   Set S_u to 0.

b) Using the multimode-reference technique

   Find I_u and S_u by simplex regression so that the sum of the absolute values of error is minimum, and such that all errors are non-negative.

   Determine the median of the errors and add the value to I_u.

D.2.5 Step 3: calculate the deviation of the spectral transmittance from the linear fit

Define a function, $d(\lambda)$, to represent the difference between the transmittance and the linear fit of the upper wavelength region, using Formula (D.2).

$$d(\lambda) = A(\lambda) - I_u - S_u\lambda \quad \text{(D.2)}$$

where

$d(\lambda)$	is the function representing the difference between transmittance and linear fit (dB);
$A(\lambda)$, I_u and S_u	are as defined in Formula (D.1).

D.2.6 Step 4: determine the end wavelength of the transition region

The transition region starts at a wavelength ("start wavelength", λ^t_{start}) and ends at a higher wavelength ("end wavelength", λ^t_{end}).

One method to identify the end wavelength λ^t_{end} is by adding 10 nm to the maximum wavelength at which the function $d(\lambda)$ is greater than 0,1 dB.

D.2.7 Step 5: determine the start wavelength of the transition region

There are various ways to determine the start wavelength λ^t_{start}. Here are two examples.

a) Starting with the end wavelength λ^t_{end} from step 4, find the wavelength at which $d(\lambda)$ has a local maximum, and the difference between this maximum and the next local minimum (at larger λ) is maximum.

b) Find the largest wavelength, below the end wavelength λ^t_{end}, such that $d(\lambda)$ is greater than 2 dB and:

- there is a local maximum for $d(\lambda)$, or
- there is a local maximum for $d(\lambda) - d(\lambda + 10\ \text{nm})$.

D.2.8 Step 6: characterize the transition region with the theoretical model

The model is a linear regression of a transformation:

$$Y(\lambda) = 10\log_{10}\left[-\frac{10}{C}\cdot\log_{10}\left(\frac{10^{\frac{d(\lambda)}{10}}-1}{\rho}\right)\right] \tag{D.3}$$

where

$Y(\lambda)$ is the transformation function.

C is defined by Formula (D.4):

$$C = 10\cdot\log_{10}\left[\frac{\rho}{10^{0,01}-1}\right] \tag{D.4}$$

where

ρ = 2, unless otherwise specified.

$d(\lambda)$ is defined in Formula (D.2) and used for wavelengths in the transition region.