BS EN 60793-1-20:2014

BSI Standards Publication

Optical fibres

Part 1-20: Measurement methods and test procedures — Fibre geometry

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National foreword

This British Standard is the UK implementation of EN 60793-1-20:2014. It is identical to IEC 60793-1-20:2014. It supersedes BS EN 60793-1-20:2002 which is withdrawn.

The UK participation in its preparation was entrusted by Technical Committee GEL/86, Fibre optics, to Subcommittee GEL/86/1, Optical fibres and cables.

A list of organizations represented on this committee can be obtained on request to its secretary.

Published by BSI Standards Limited 2014

ISBN 978 0 580 83647 3
ICS 33.180.10

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 December 2014.

Amendments issued since publication

Date	Text affected

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN 60793-1-20

November 2014

ICS 33.180.10

Supersedes EN 60793-1-20:2002

English Version

Optical fibres - Part 1-20: Measurement methods and test procedures - Fibre geometry (IEC 60793-1-20:2014)

Fibres optiques - Partie 1-20: Méthodes de mesure et
procédures d'essai - Géométrie de la fibre
(CEI 60793-1-20:2014)

Lichtwellenleiter - Teil 1-20: Messmethoden und
Prüfverfahren - Fasergeometrie
(IEC 60793-1-20:2014)

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Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

CEN-CENELEC Management Centre: Avenue Marnix 17, B-1000 Brussels

Ref. No. EN 60793-1-20:2014 E

Foreword

The text of document 86A/1562/CDV, future edition 1 of IEC 60793-1-20, prepared by SC 86A "Fibres and cables" of IEC/TC 86 "Fibre optics" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 60793-1-20:2014.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2015-08-14
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2017-11-14

This document supersedes EN 60793-1-20:2002.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 60793-1-20:2014 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following note has to be added for the standard indicated :

IEC 60793-1-45	NOTE	Harmonized as EN 60793-1-45.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE 1 When an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

Publication	Year	Title	EN/HD	Year
IEC 60793-2-10	-	Optical fibres - Part 2-10: Product specifications - Sectional specification for category A1 multimode fibres	EN 60793-2-10	-
IEC 60793-2-20	-	Optical fibres - Part 2-20: Product specifications - Sectional specification for category A2 multimode fibres	EN 60793-2-20	-
IEC 60793-2-30	-	Optical fibres - Part 2-30: Product specifications - Sectional specification for category A3 multimode fibres	EN 60793-2-30	-
IEC 60793-2-40	-	Optical fibres - Part 2-40: Product specifications - Sectional specification for category A4 multimode fibres	EN 60793-2-40	-
IEC 60793-2-50	-	Optical fibres - Part 2-50: Product specifications - Sectional specification for class B single-mode fibres	EN 60793-2-50	-
IEC 60793-2-60	-	Optical fibres - Part 2-60: Product specifications - Sectional specification for category C single-mode intraconnection fibres	EN 60793-2-60	-
IEC 61745	-	End-face image analysis procedure for the calibration of optical fibre geometry test sets	-	-

CONTENTS

INTRODUCTION

This standard gives two methods for measuring fibre geometry characteristics:

– Method A: Refracted near-field, described in Annex A;

– Method B: Transmitted near-field, described in Annex B.

Methods A and B apply to the geometry measurement of all class A multimode fibres, class B single-mode fibres and class C single-mode interconnection fibres. The fibre's applicable product specifications, IEC 60793-2-10, IEC 60793-2-20, IEC 60793-2-30, IEC 60793-2-40, IEC 60793-2-50 and IEC 60793-2-60, provide relevant measurement details, including sample lengths and k factors.

The geometric parameters measurable by the methods described in this standard are as follows:

– cladding diameter;

– cladding non-circularity;

– core diameter (class A fibre only);

– core non-circularity (class A fibre only);

– core-cladding concentricity error.

NOTE 1 The core diameter of class B and class C fibres is not specified. The equivalent parameter is mode field diameter, determined by IEC 60793-1-45.

NOTE 2 These methods specify both one-dimensional (1-D) and two-dimensional (2-D) data collection techniques and data analyses. The 1-D methods by themselves cannot detemine non-circularity nor concentricity error. When non-circular bodies are measured with 1-D methods, body diameters suffer additional uncertainties. These limitations may be overcome by scanning and analysing multiple 1-D data sets. Clause 5 provides further information.

Information common to both methods appears in Clauses 2 through 10, and information pertaining to each individual method appears in Annexes A and B, respectively. Annex C describes normative methods used to find the optical boundaries of the core and the cladding, Annex D describes normative procedures to fit ellipses to sets of detected boundaries. Annex E provides an informative fitting procedure of power-law models to graded-index core profiles. Annex F describes an informative methodology relating to the transformation of core diameter measurements determined with methods other than the reference method to approximate reference method values.

OPTICAL FIBRES –

Part 1–20: Measurement methods and test procedures – Fibre geometry

1 Scope

This part of IEC 60793 establishes uniform requirements for measuring the geometrical characteristics of uncoated optical fibres.

The geometry of uncoated optical fibres directly affect splicing, connectorization and cabling and so are fundamental parameters requiring careful specification, quality control, and thus measurement.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60793-2-10, *Optical fibres – Part 2-10: Product specifications – Sectional specification for category A1 multimode fibres*

IEC 60793-2-20, *Optical fibres – Part 2-20: Product specifications – Sectional specification for category A2 multimode fibres*

IEC 60793-2-30, *Optical fibres – Part 2-30: Product specifications – Sectional specification for category A3 multimode fibres*

IEC 60793-2-40, *Optical fibres – Part 2-40: Product specifications – Specification for category A4 multimode fibres*

IEC 60793-2-50, *Optical fibres – Part 2-50: Product specifications – Sectional specification for class B single-mode fibres*

IEC 60793-2-60, *Optical fibres – Part 2-60: Product specifications – Sectional specification for category C single-mode intraconnection fibres*

IEC 61745, *End-face image analysis procedure for the calibration of optical fibre geometry test sets*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the following terms, definitions and symbols apply:

3.1.1
body
general term describing an entity whose geometry is measured (i.e. cladding or core)

3.1.2
reference point
fixed coordinate in the scan's plane

Note 1 to entry: This point is arbitrary (say the lower left corner of a video image, or the rough centre of the fibre after the fibre is located in a scanning apparatus).

3.1.3
centre
centre of a body in the measurement plane with respect to the reference point, expressed in micrometres

3.1.4
diameter
average diameter, in micrometres, of a nearly circular body

3.1.5
non-circularity
difference between the maximum and minimum radial deviation from the body's centre, normalized to the body's diameter, expressed as a per cent

3.1.6
concentricity error
scalar distance, in micrometres between two body centres

3.1.7
scan
term used to define the collection of data along one axis of the Cartesian coordinate plane, at a fixed angular orientation and a fixed offset from the reference point

3.1.8
scan set or set
one or more scans used together to determine the fibre's geometry

Note 1 to entry: The set can be one scan (see limitations below), a set of scans at different angular orientations with respect to the fibre, or a raster scan (like a video image).

3.1.9
edge table
set of number pairs representing a set of points in the scanning plane which define a closed curve line of delineation between the cladding and the surrounding media (the cladding edge table) or the core and the cladding (the core edge table)

3.1.10
elliptical model
ellipse fit
best fit ellipse to an edge table

3.2 Symbols

The symbols defined below are used to indicate various aspects of a scanned data set. Scans can be one-dimensional, or two-dimensional raster scans (where the scan axes are orthogonal on a Cartesian plane), or a set of one-dimensional scans at a set of angles.

i The index used for the scanning axis or the 'fast' axis in the case of a raster scan.

j The index used for the 'slow' axis in a raster scan.

k The index used for the angle in a multi-angular scan set.

I The set of data from one-dimensional or two-dimensional scanning. The data can be near-field intensity data (from Method B) or index of refraction (Method A); in this standard, no delineation is made as either type of data is intermediate and is further analysed to extract the fibre’s geometry. A single datum from a set is indicated by subscript in a manner consistent with the nature of the data set: I_i for the ith point of the scan in a single scan set; $I_{j,i}$ for a raster data point at the jth location on the slow axis and the ith position on the fast axis; $I_{k,I}$ for the i^{th} point at the k^{th} angle.

x	The positional data, in micrometres, of the set. For a single scan set, the meaning of x is clear. For a raster scan set or a multi-angle set, x refers to the positional data of the ‘fast’ axis (raster) or scan positions (for each angle). (Raster sets whose individual lines have different fast-axis positions or multi-angle sets where each angle uses a different set of positions are allowed by this standard, but this complication is ignored in the forthcoming analytical development).
y	The positional data, in micrometres, of the raster lines (the slow-axis locations) in a raster scan set.
φ	The angles in a multi-angle set. The k^{th} angle in the set is indicated by subscript: φ_{k}.
nS	The number of points in a single scan. In the case of raster scan sets n_{S} is the number of points of the fast axis. In multi-angular scan sets, nS is the number of points in any scan. (This standard’s nomenclature ignores cases where the number of points varies between raster lines or angles, although such data sets are allowed.)
nR	The number of raster rows (slow axis scans) in a raster set.
$n\varphi$	The number of angles in a multi-angle set.

NOTE The following symbols are used to describe an edge table.

X,Y	A set of locations in the X-Y scan plane of the fibre which delineate a body from its surroundings.
n_{e}	The number of edge points in an edge table.

4 Overview of method

4.1 General

In essence, each method (A or B) defined herein describes a way of producing an image of the fibre in a plane normal to its axis of propagation. This resultant image is then further analysed (as described in Annexes C, D and E) to reduce the image to an expression of the fibre’s geometry. Methods A and B can produce images which are one-dimensional (i.e. along only one axis in the plane of the image), or two-dimensional. It is obvious that a two-dimensional image is more information rich, and thus these images produce more complete geometric information; the non-circularity of a body cannot be determined from a one-dimensional scan, nor can concentricity errors be determined with any certainty.

The analysis of the image consists of two steps. The first step is to quantify where in the image the body of interest is delineated (see Annex C). The second step reduces the ensemble of these points of delineation to one or more geometric parameters: diameter, non-circularity and centre (if both, the cladding and core are measured and their centres determined then concentricity error may also be determined). Annex D describes methods which can be used on both the cladding and core of all fibre types and Annex E describes a method that may be used for the core body of class A fibres.

This standard addresses a range of needs, and as such, allows for a range of for data collection and reduction. The specific limitations and uses of these approaches are discussed below.

4.2 Scanning methods

4.2.1 General

As noted above, sampling a two-dimensional body in only one-dimension has limitations. Ideal fibres are perfectly circular and the core and cladding are concentric; real fibres are noncircular and have concentricity errors. Non-circularity and concentricity cannot be measured by a one-dimensional scan and one-dimensional scanning may under- or over-estimate the average diameter of a noncircular body. One-dimensional scanning may be useful for fibres whose non-circularity and concentricity errors are known to be small and one-dimensional scans are commonly used to determine the core diameter of class A fibres.

4.2.2 One-dimensional scan sources of error

4.2.2.1 Scanning a chord

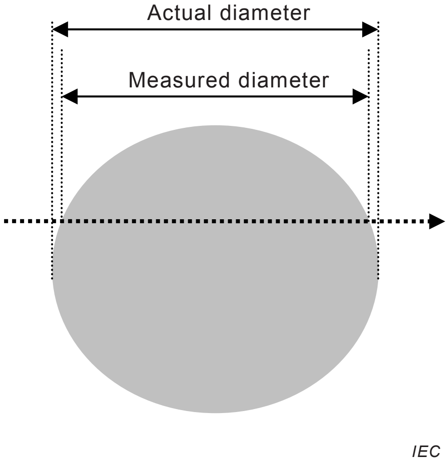
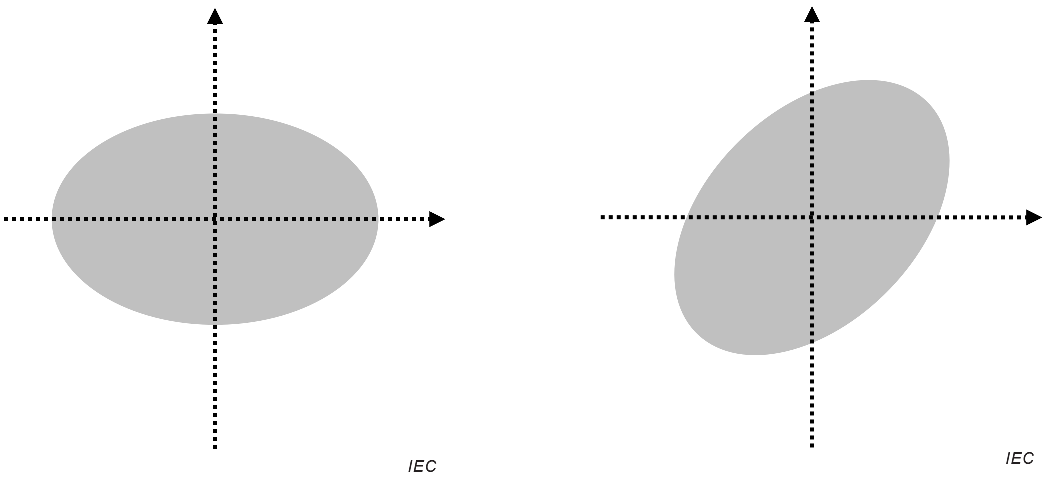


Figure 1 – Sampling on a chord

Figure 1 illustrates the error that occurs when the sampling axis is not co-linear with the centre of the body. When the sampling axis misses the body’s centre, the body’s diameter is underestimated. This is a second order error.

4.2.2.2 Scanning non-circular bodies

If a body is non-circular, a one-dimensional scan will not fully describe the body’s shape. Sampling a body in one dimension will generally under-estimate or over-estimate the average diameter of the body. It may be assumed that this problem can be rectified by sampling the body in two orthogonal axes (i.e. X and Y), but in general, this is not sufficient. Consider Figure 2:



Figre 2a – Major diameter **Figure 2b – Average diameter**

Figure 2 – Scan of a non-circular body

Figure 2 illustrates errors that occur when an elliptical body is sampled on one or two axes. In the major diameter example (Figure 2a), the ellipse's major diameter is aligned with the X axis. In this case, sampling only in X will over-estimate the body's average diameter; the fact that the body is non-circular will be missed (likewise, sampling the body only in Y will underestimate the body's diameter). In this orientation, if the body is sampled on both axes the body will be completely characterized: both its average diameter and non-circularity are discovered. However, in the 'average diameter' case, sampling on either axes gives the same, approximately correct diameter for both axes; if both axes are sampled it would appear that the body is perfectly circular. Analysing ±45 ° scans will give the correct non-circularity and diameter, but there is no way to know the proper angular scan angles beforehand. At orientations other than –45 ° and +45 °, the body's average diameter will be measured correctly, but the body's circularity will be underestimated.

4.2.2.3 Concentricity indeterminacy

If a single axis is scanned, the core's centre relative to the cladding centre cannot be known. Scanning two orthogonal axes can provide a reasonable estimate of the core's centre. This estimate will degrade if the core is scanned on a chord far from the core's centre. If the core is substantially smaller than the cladding and is significantly non-concentric, then one or more scans may miss the core entirely.

4.2.3 Multidimensional scanning

4.2.3.1 Multi-angle scanning

As suggested in 5.2.2.2 and 5.2.2.3, the estimation of the geometry of the fibre can be improved by scanning on two orthogonal axes. Combining scans over more than two angles (for example at 0 °, 45 °, 90 ° and 135 °) will improve these estimates further. Acquiring data at multiple angles can be accomplished by rotating the fibre in its holding chuck, or, if the scanner is so designed, by the mechanics of the scanner itself. Note that all angular scans shall share a single frame of reference (a common origin) or errors will be introduced.

4.2.3.2 Raster scanning

If the scanner is capable of motion on two orthogonal axes, then it is possible that a two-dimensional image of the fibre may be constructed by performing a raster scan.

Measurement of the transmitted near-field using grey-scale video is inherently a raster scan.

4.3 Data reduction

4.3.1 Simple combination of few-angle scan sets

When reducing data sets where only a few angular orientations are measured, it is generally sufficient to employ simple data reduction. For each body, the diameter can be determined by averaging the diameters of each angular scan; the non-circularity by using the maximum and minimum diameters from the set of angles. When both cladding and core are measured, the concentricity error can be determined simply from the angle showing the worst-case centration error. See Annex D for more information.

4.3.2 Ellipse fitting of several-angle or raster data sets

When many data points may be extracted from the scan set, as is the case when many angles are scanned or when raster scanning is employed, the edge tables may be fit to elliptical models. Annex E describes the methodology to fit a body's edge table (determined as described in Annex D).

For both the cladding and the core for all fibre categories, ellipse fitting is the reference method.

5 Reference test method

The reference test method (RTM) is the video grey-scale transmitted near-field method described in Annex B for all fibre categories. Data analysis shall employ boundary detection as described in Annex C, and ellipse fitting to reduce the edge tables to geometry, as described in Annex D. See Annexes A and B for a discussion of reference sample lengths for all fibre classes, and refer to Annex C for a discussion of the decision threshold factor k for class A fibres.

6 Apparatus

Annexes A and B include layout drawings and other equipment requirements for each of the Methods A and B, respectively.

7 Sampling and specimens

7.1 Specimen length

Annexes A and B specify the required sample lengths for their respective methods.

7.2 Specimen end face

Prepare a clean, flat end face, perpendicular to the fibre axis, at the input and output ends of each specimen. The accuracy of measurements is affected by a non-perpendicular end face. End angles less than 1 ° are recommended.

See Clause B.2 for the tighter requirements on end faces when using Method B.

8 Procedure

Use the procedures given in IEC 61745 for calibration. Annexes A and B document the procedures for Methods A and B, respectively.

9 Calculations

Refer to Annexes C, D and E for details regarding the calculations.

10 Results

The following information shall be provided with each measurement:

- date and title of measurement;
- identification and description of specimen;
- measurement results for each parameter specified (see the applicable annex).

The following information shall be available upon request:

- measurement method used: Method A or B;
- specimen length;
- arrangement of measurement set-up;
- details of measurement apparatus (see applicable annex);
- relative humidity and ambient temperature at the time of the measurement;
- most recent calibration information.

11 Specification information

The detail specification shall specify the following information:

- type of fibre 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 – Refracted near-field

A.1 Introductory remarks

The refracted near-field measurement directly measures the refractive index variation across the fibre (core and cladding). The method can be calibrated to give absolute values of refractive indices. It can be used to obtain profiles of both single-mode and multimode fibres. A refracted near-field measurement determines the radial dependence of relative index variations of a fibre by scanning a spot of light across its end-face. If a theoretical ray of light could be generated, then changes in index could be detected by injecting the ray into the fibre at an angle greater than the maximum numerical aperture of the fibre and measuring its exit angle. Since an ideal ray cannot be generated and since the fibre's physical dimensions are of the order of 100 optical wavelengths, an integral approach using an angular bundle of rays is taken. A small spot of light with a numerical aperture greater than the fibre's is scanned across the end-face of a fibre at a normal angle of incidence. The light cone which exits the fibre is then sampled at a small range of high angles (i.e. greater than the numerical aperture). The total power in this sampled region is then determined as a function of the radial location of the launch spot. As the light traverses the local index differences in the fibre, it refracts, changing its exit angle. Light that passes through the core and then the cladding will exit the fibre at shallower angles than light that passes solely through the cladding. Since only high angle light is sampled, the core region's total detected power will be lower than the cladding. The relative power at a given scan position is thus directly proportional to the fibre's index at that position.

A.2 Apparatus

A.2.1 Typical arrangement

See Figures A.1 and A.2 for schematic diagrams of the test apparatus.

A.2.2 Source

Provide a stable laser giving a few milliwatts of power in the TEM_{00} mode.

A HeNe laser, which has a wavelength of 633 nm, may be used, and for geometrical measurements is sufficient. If the index is to be measured (not specified by this standard) a correction factor may be required to extrapolate the results for other wavelengths.

Introduce a quarter-wave plate to change the beam from linear to circular polarization to produce a time-averaged signal independent of polarization effects due to reflectance the reflectivity of light at an air-glass interface is strongly angle and polarization-dependent.

If necessary, place a spatial filter, such as a pin-hole, at the focus of the microscope objective.

A.2.3 Launch optics

Arrange the launch optics, often a high magnification, high numerical aperture microscope objective, to overfill the numerical aperture (NA) of the fibre. This brings 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 spatial resolution of the equipment is limited by the size of the focused spot and so should be made as small as possible, e.g. less than 1,5 μm.

A.2.4 *XYZ* positioner (scanning stage)

Either the launch optics or the cell shall be mounted on a three-axis positioner capable of motion larger than the expected fibre diameter. The resolution of the focus axis (Z) shall be sufficient to ensure that the focus of the spot on the fibre end-face is sharp enough to not materially impair the spatial resolution of the instrument. The resolution of the other two axes (X and Y) shall be smaller than half the focused spot size.

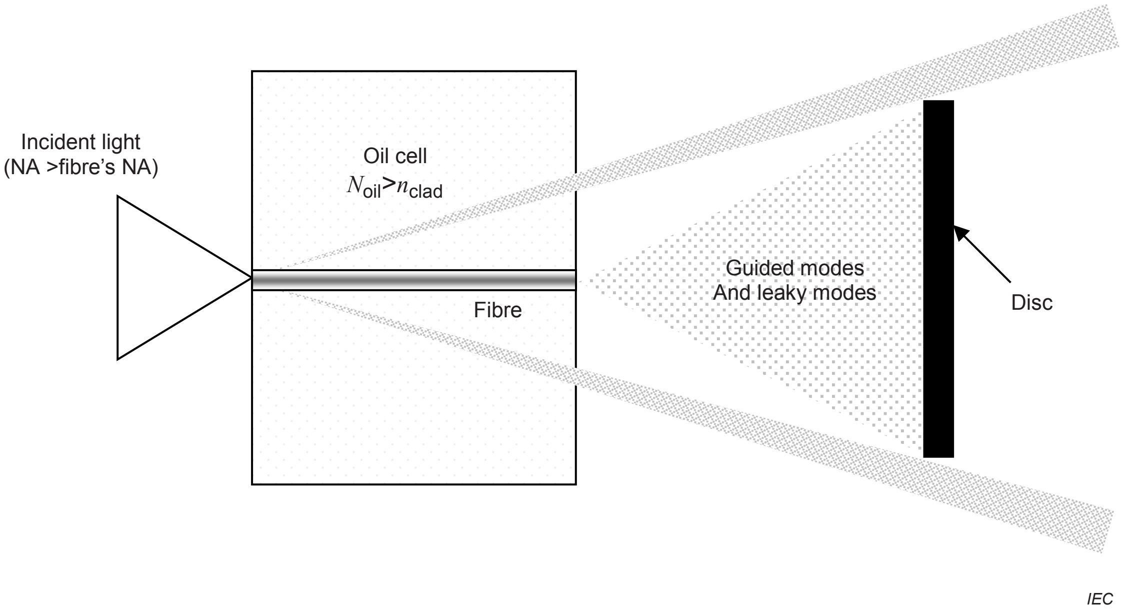


Figure A.1 – Refracted near-field method – Cell

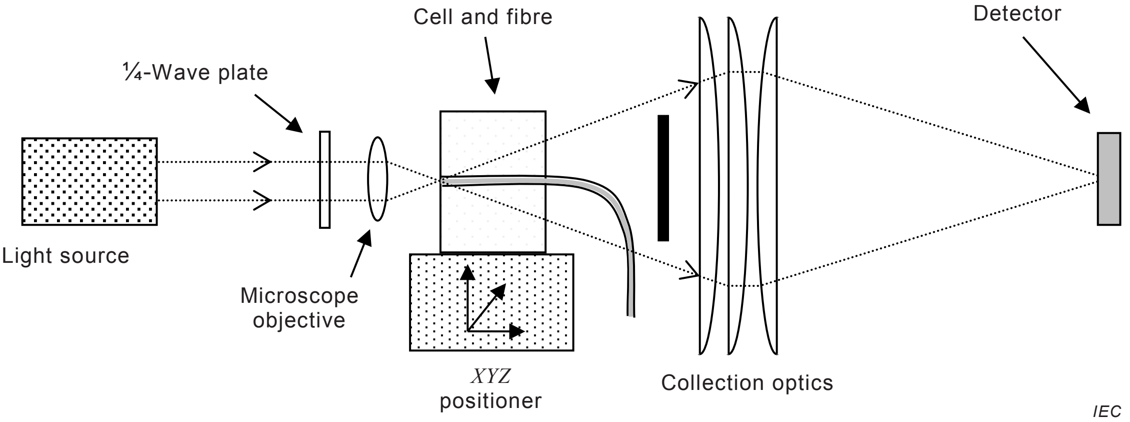


Figure A.2 – Typical instrument arrangement

A.2.5 Blocking disc

The blocking disc's purpose is to ensure that only light which passes into the fibre and refracts out of the fibre without internal reflection or guidance inside the fibre reaches the detector. The fibre itself can play part of the role of the blocking disc by making it long enough to bend out of the optical path, taking any guided light with it, but this is not sufficient. Partial internal reflection will cause some of the light at the cladding/oil interface to be reflected back into the fibre. When non-refracted light reaches the detector, the measured power will increase, causing a corresponding negative error in index determination.

The blocking disc prevents a subtended angular cone of light from reaching the detector and should be selected so that the predominant fraction of non-refracted light is blocked, but not block so much of the refracted light that the signal-to-noise performance of the instrument is degraded. Typically, the subtended cone's NA is selected to be approximately the light source's NA at the fibre end-face, divided by $\sqrt{2}$.

A.2.6 Collection optics and detector

It is essential that the total power of the light passing the blocking disc be measured. Large condenser lens systems, parabolic and elliptical mirrors, large area detectors, integrating spheres and other means may be employed. A practical implementation will need to trade off the size of the detector and optical complexity. The combination should ensure that the total light power is measured up to the NA launched into the fibre; the detector's noise and dynamic response shall not seriously impair the measurement.

The detector itself shall be responsive to the wavelength of the light source and be sufficiently linear for the range of expected optical power levels. Amplifiers and data converters are typically coupled to the detector to condition the detector's signal and measure the relative differences automatically as the stage is scanned.

A.2.7 Computer system

A computer is used to collect data by controlling the positioner and digitizing the detector signal. Once the data is collected, the computer converts the detector signal to index difference (or absolute index) by applying the appropriate calibration.

A.2.8 Immersion cell

The immersion cell is the environment around which the fibre is held and ensures that the light exiting the fibre encounters an index high enough that no light is coupled back into the fibre through total or partial reflection. It is paramount that the optical media surrounding the cladding be of an optical refractive index higher than the cladding. Index matching oils are used to accomplish this purpose. The cell itself can be of any design which does not materially affect the refraction of the rays into the collection optics.

A.3 Sampling and specimens

The length of the fibre sample is dependent on the instrument design. In no case shall the output end of the fibre, (the end not in the scanning plane of the instrument) be allowed to couple light into the detector.

Remove all fibre coatings from the section of fibre to be immersed in the liquid cell.

A.4 Procedure

A.4.1 Load and centre the fibre

Place the fibre sample in the cell and locate the rough fibre centre, X_f, Y_f, which can be determined by a method such as back illumination with a tungsten lamp, or by scanning the XY stage to search for the fibre. Adjust the stage to centre and focus the source spot on the fibre end.

If required by the instrument design, centre the disc on the output cone. For class A multimode fibre, position the disc on the optical axis to just block the leaky modes. For class B and C single-mode fibres, position the disc to give optimum resolution.

Once the fibre is centred and the disc is aligned, either line scans or a complete raster scan can be performed.

A.4.2 Line scan

Scan the stage at an angle of interest, φ: at 0 ° using only the X stage, at 90 ° using only the Y stage, or any appropriate angle, using both stages (the stage resolution and the desired scan resolution will restrict which angles can be scanned). The range of the scan should extend beyond the cladding on both sides of X_f, Y_f. The radial spacing of the scan should be selected such that the index variation is sampled sufficiently to determine the fibre's geometry with the required accuracy. A set of nS power readings is collected

where

P_i is the set of detected power readings;

x_i is the set of radii where the power readings were collected.

A.4.3 Raster scan

Scan the stage over both the X and Y axes in a raster pattern over a range sufficient to encompass the cladding in both axes. The spacing of both the X and Y scans should be selected such that the index variation is sampled sufficiently to determine the fibre's geometry with the required accuracy. A set of power readings is collected

where

$P_{j,I}$ is the set of detected power readings,

x_i is the set X-axis points where the power readings were collected,

y_j is the set Y-axis points where the power readings were collected.

A.4.4 Calibration

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 liquid 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, the profile can be scaled in terms of relative index, determining the instruments delta calibration factor, K_{Δ}. Absolute indices, i.e. n_1 and n_2, can only be found if the cladding index or the liquid index, at the measurement wavelength and temperature, is known accurately.

The geometric scaling factors, S_X and S_Y (in units of micrometres per stage step), of the scanning stage shall also be determined. They can be determined by scanning a traceable artefact such as a chrome-on-glass reticule, or by certification of the stage micrometers or indexers, or by other appropriate means.

A multi-index calibration artefact, which may be made available from national standards institutes, may also be used to determine K_{Δ}, S_X and S_Y.

A.5 Index of refraction calculation

Determine relative index profile, Δ_i (or alternatively $\Delta_{i,j}$ for a raster scan).

$$\Delta_i = K_{\Delta}(P_{\text{ref}} - P_i) \tag{A.1}$$

where P_{ref} is a reference power level that determines where in the profile the index difference difference is zero. This can be any convenient point in the profile, or can be an instrument parameter. Its value does not affect the subsequent calculations.

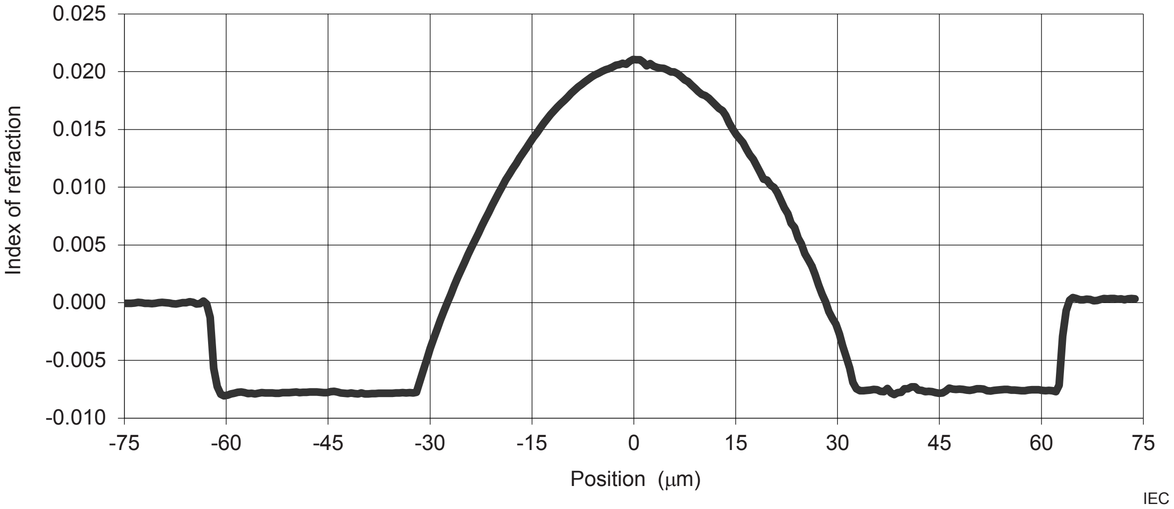


Figure A.3 – Typical index profile line scan of a category A1 fibre

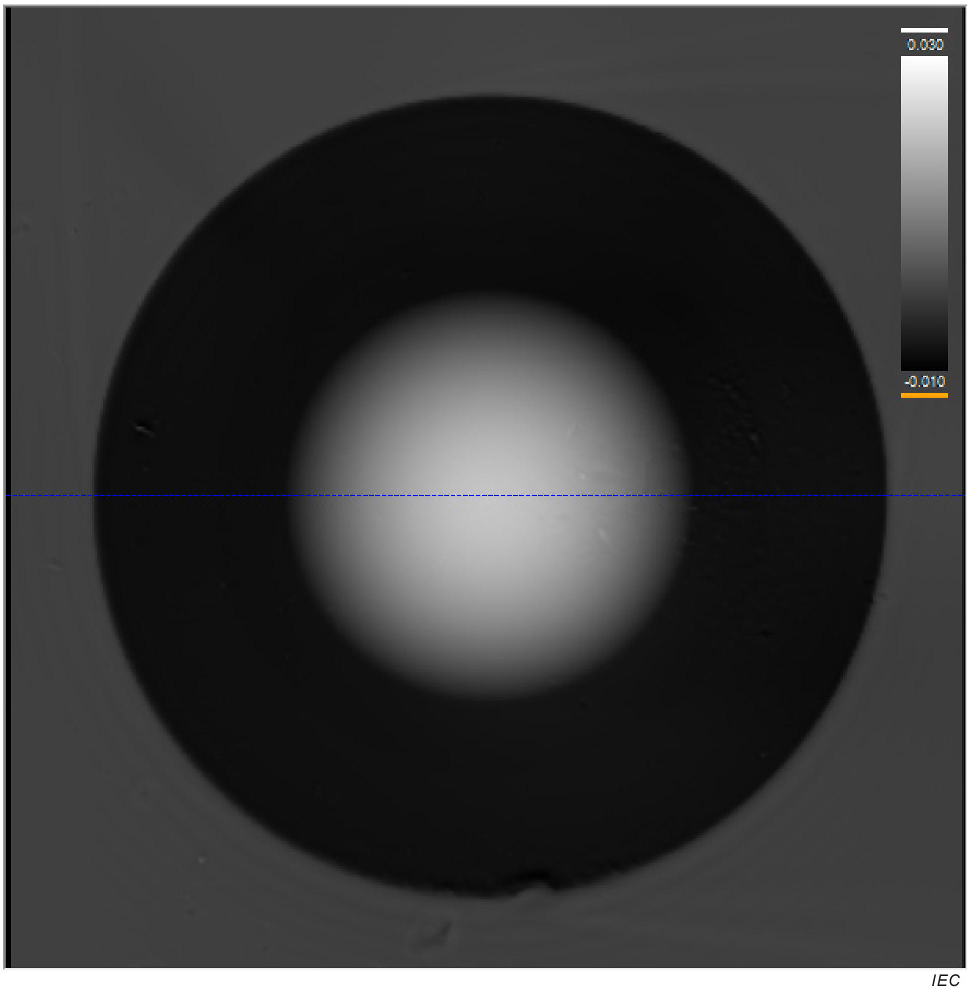


Figure A.4 – Typical raster index profile on a category A1 fibre

Figure A.3 and A.4 show typical index profile data of a category A1 fibre. Figure A.4 expresses the index of refraction as a grey-level of intensity, with whiter colours indicating higher index.

A.6 Calculations

Refer to Annexes C, D and E to reduce the index scan set to geometry, substituting Δ for I.

A.7 Results

The following parameters may be determined from the measurement:

- core diameter (class A multimode fibres only);
- cladding diameter;
- core/cladding concentricity error;
- core non-circularity (of type A fibre);
- cladding non-circularity;
- maximum theoretical numerical aperture;
- index difference;
- relative index difference.

In addition to the results listed in Clause 11, and depending on the specification requirements, the following information shall be provided on request:

- profiles at specific angles calibrated for a given wavelength;
- equipment arrangement and wavelength correction procedure.

Annex B
(normative)

Requirements specific to Method B – Transmitted near-field

B.1 Introductory remarks

The transmitted near-field method determines geometric parameters of class A multimode fibres and class B and C single-mode fibres by analysing the optical power density as a function of position on a cross-section at the end of the fibre under test. There are two techniques described in this annex; both analyse the near-field image of an optical fibre end-face:

- the video grey-scale technique, employing a video camera to analyse the image two-dimensionally;
- the mechanical scan technique, in which one or more one-dimensional scans of the image are acquired for analysis.

The video grey-scale technique is the reference test method (RTM).

One-dimensional mechanical scanning is often used to measure the core diameter of class A multimode fibres. As discussed in Clause 5, one-dimensional scans have limitations when used by themselves. Multiple one-dimensional scans may be combined through the data reduction techniques of Annexes C and D to overcome these limitations at the expense of additional measurement time and complexity. Typically, one-dimensional near-field scanning is used for the determination of core diameter of class A multimode fibres.

B.2 Apparatus

B.2.1 Typical arrangement

Figures B.1 and B.2 are examples of apparatus configuration for the two techniques.

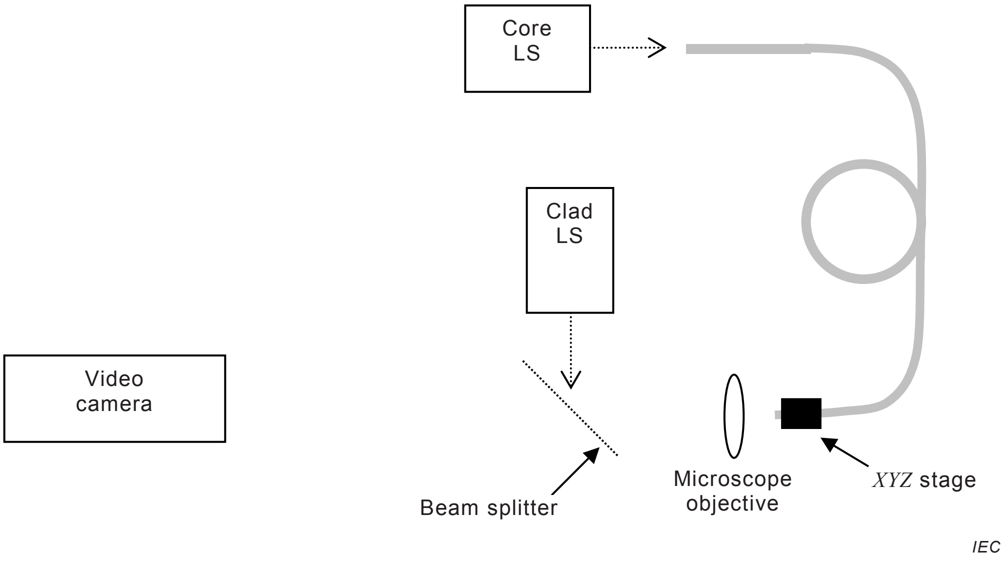


Figure B.1 – Typical arrangement, grey scale technique

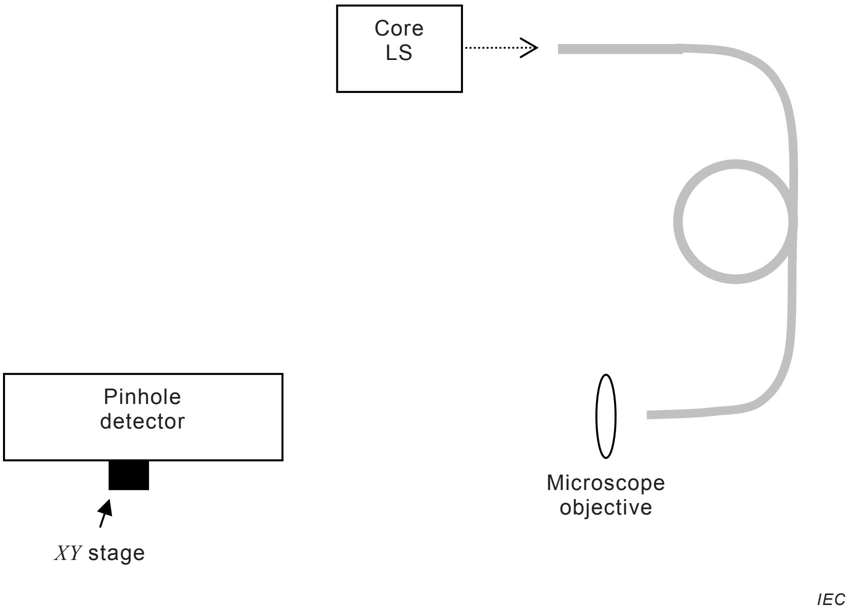


Figure B.2 – Typical arrangement, mechanical scanning technique

B.2.2 Light sources

B.2.2.1 General

Use suitable incoherent light sources for the illumination of the core and the cladding, adjustable in intensity and stable in intensity over a time period sufficient to perform the measurement.

B.2.2.2 Core illumination requirements

Class A multimode fibres' core geometry shall be determined using incoherent illumination which angularly and spatially overfills the core at the operational wavelength of the fibre, unless otherwise agreed. Class B and C single-mode fibres' core centre is determined by this technique, but core diameter and circularity are not. Therefore, the core illumination requirements for class B and C fibres are more relaxed: the wavelength can be any wavelength that is convenient to the design of the instrument and shall overfill the one to few modes propagating in the fibre at that wavelength. The implicit assumption is that class B and C core centre does not substantially change with wavelength even when more than one mode group propagates in the core.

Unless otherwise specified in the product specification, category A1, A2 and A3 multimode fibres' geometry shall be determined with a core illumination centre wavelength of 850 nm ±10 nm. Unless otherwise specified in the product specification, category A4 fibres' geometry shall be determined with a core illumination centre wavelength of 650 nm ±10 nm. The full-width-half-maximum width of the core illuminators for all class A fibres shall be greater than 10 nm and less than 50 nm.

At the time of writing, all class A fibre specifications were being revised, partially to include the centre wavelength used to determine core geometry. Once these specifications are published, including this information, the preceding paragraph shall be ignored and the information in the product specification be used in its place.

B.2.2.3 Cladding illumination requirements

The cladding can either be illuminated in a dark field, that is, with light reflecting off the fibre's cleaved end-face thus leaving the air surrounding the cladding unlit, or inversely, the surrounding air may be flooded with light leaving the cladding un-illuminated. The illumination wavelength is unimportant but its relationship to the core illuminator's wavelength shall be considered with respect to the dispersion of the magnifying optics: selecting a similar wavelength or at least a wavelength inside the performance window of the optics will ensure that the core will not become defocused when the cladding is in focus.

If this method is used only to determine the core diameter of class A fibres, then usually the cladding will not be illuminated during measurement. For the video grey-scale technique, it is also allowable that the core diameter and non-circularity are determined using an image or scan with the cladding un-illuminated, and a second illuminated cladding image used to determine all other parameters.

B.2.3 Fibre support and positioning apparatus

Provide a sufficiently stable means of supporting the specimen input and output ends, for example, a vacuum chuck. Mount these supports on positioning devices so the fibre ends can be accurately positioned in the input and output paths. It may be convenient to have the support apparatus mounted to three-axis translation stages (these stages may take the role of the scanner in some embodiments of the mechanical scanning technique.)

B.2.4 Cladding mode stripper

Unless otherwise specified, use devices that strip cladding mode light from the specimen reasonably near the fibre input and output ends. When the fibre under test has a coating layer in contact with the cladding whose refractive index is higher than that of the glass, this coating acts as the cladding mode stripper.

B.2.5 Detection

B.2.5.1 General

For both techniques, it is necessary that the detection system be sufficiently linear to not impact the required measurement precision. PIN photodiodes in photovoltaic mode and modern camera sensors will generally satisfy this requirement, but care shall be taken in their selection and use. High levels of illumination can degrade the performance of these detectors as can poorly designed conditioning electronics and digitization systems.

B.2.5.2 Grey-scale detector

For the video grey-scale technique, use a video camera to detect the magnified output near-field image. A video digitizer performs the digitization of the image for analysis (often, the camera and digitizer are combined into one element). The digitized output will be an pixel array of near-field intensities, $I(r,c)$, over N_{Row} rows and N_{Col} columns. Both CCD and CMOS imaging sensors are appropriate for this application. The effective pixel size shall satisfy Equation (B.1).

The precision of the measurement can be degraded by systematic errors present in the detection system. Examples of these errors include the geometric uniformity of the resultant digitized image or the linearity of the detector/digitizer with respect to changes in optical intensity. Attention shall be paid to these and other potential errors; IEC 61745 provides the methodology required to determine the magnitude of these errors.

B.2.5.3 Mechanical scan detector and scanner

The mechanical scan detector uses a fixed-aperture detector and a scanning system to acquire the intensity of the image as a function of position. The mechanical scanner provides a means of scanning the focused image of the fibre near-field pattern; the scanner is calibrated in such a way that relative radial position in known. If the apparatus employs a very high resolution mechanical scanner it is possible to move the fibre or, equivalently, the imaging system and detector together. Another approach is to scan the detector in the image plane, allowing the use of a lower-resolution mechanical scanner. In any case, the mechanical scanner shall be linear enough to satisfy the required measurement precision.

The detector's effective aperture shall be limited to satisfy Equation (B.1). A detector with a small active area (i.e. a 20 μm diameter detector used in conjunction with a 40X imaging system) can satisfy this requirement. The aperture can be restricted using an optical fibre with a sufficiently small core diameter whose input end is in focus in the image plane, and whose output is coupled to the detector. A mechanical pinhole may also be employed for this purpose (in this case, relay optics may be employed to image the back side of the pinhole onto the optical detector.)

B.2.6 Magnifying optics

B.2.6.1 Optical imaging system general information

Provide a suitable imaging system that magnifies the output near-field image of the specimen so that this magnified image can be suitably scanned. The numerical aperture of this imaging system shall be greater than the numerical aperture of the core of the fibre to be measured. The numerical aperture of the imaging system affects the resolving power of measurement, and thus shall be compatible with the measuring accuracy, and not lower than 0,3.

The pixels' largest dimension in the video grey-scale technique or the size of the detector (or pin-hole) in the mechanical scan technique shall be sufficiently small compared with the magnified near-field image as to be less than the system diffraction limits by a factor of 2. That is:

$$d \leq \frac{1{,}22\ M\lambda}{4\ \mathrm{NA}} \tag{B.1}$$

where

d is the pixel size of the camera, or the detector (pin-hole) size in μm;

M is the approximate magnification of the optical system;

λ is the (lowest) test wavelength in μm;

NA is either the numerical aperture of the fibre's core for core diameter-only measurements of class A fibres, or, for all other applications, the numerical aperture of the objective (assuming the cladding illuminator completely fills the optical system in NA).

Calibrate the optical system in conjunction with the scanning system so that the system magnification is known. Knowing the magnification of the imaging optics (i.e. stamped on the side of a microscope objective) is not relevant since the scanning system (either the pixel spacing in the grey-scale microscope or the step size of the mechanical scanner) is also part of the system magnification and thus shall be calibrated.

B.2.6.2 Considerations for the video grey-scale technique

When using the video grey-scale technique, select the magnification so that the area of the sensor video camera is sufficiently filled by the image for the object to be measured (i.e. the cladding of the fibre when cladding and core are to be measured, or the core of the fibre when core-only measurements are made.) Ensure that the effective pixel size satisfies the requirements of Equation (B.1).

Both the X and Y axes shall be calibrated, and these calibrations are generally independent. IEC 61745 provides the methodology required to perform this calibration. The resultant calibration factors, in units of micrometres per pixel are S_X and S_Y.

B.2.6.3 Considerations for the mechanical scanning technique

When using the mechanical scanning technique, select the imaging system magnification and detector aperture size to satisfy Equation (B.1). The scanner resolution (the minimum step size) shall be no greater than one-half the diameter of the detector aperture.

The scanner shall be calibrated. The resultant calibration, in units of micrometres per step, S_X, may be arrived at using a national-laboratory traceable calibration artefact, for example, a chrome-on-glass ruler or grid of dots. If both axes of the scanner are used, then both shall be calibrated, giving two independent factors, S_X and S_Y.

B.2.7 Video image monitor (video grey-scale technique)

Use a video image monitor 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. Often, this monitor and the computer’s display are combined.

B.2.8 Computer

Use a computer to acquire the data, perform the analysis and produce the appropriate reports.

B.3 Sampling and specimens

Prepare the specimen to have fibre ends that are clean, smooth and perpendicular to the fibre axis. Typically, an end angle <1° from normal to the fibre axis is necessary for the cladding measurement. Control the end damage for minimum impact on the measurement accuracy and/or precision. Take care to avoid sharp bends when deploying the fibre.

Unless otherwise specified in the product specification, the sample length for all class A multimode fibres shall be 2 m ±0,2 m, with the exception of the bend-insensitive variants of the A1a fibres: A1a.1a, A1a.2a, A1a.3a. For these fibres, the reference test length used to resolve disputes shall be 100 ±2 m, but day-to-day measurements are allowed to use more convenient, shorter lengths. When a length other than 2 m is specified as the reference length, it is possible to map 2 m measurements onto the reference length. Mapping is explained in Annex F.

At the time of writing, all class A fibre specifications were being revised, partially to include the reference length used to determine core geometry. Once these specifications are published including this information, the preceding paragraph shall be ignored and the information in the product specification be used in its place.

There is no length restriction for class B and C single-mode fibres. Typically a 2 m sample length can be used.

B.4 Procedure

B.4.1 Equipment calibration

Artefacts traceable to a national standards laboratory shall be used to calibrate the apparatus.

B.4.2 Measurement

B.4.2.1 Measurement by the video grey-scale technique

Align the specimen at the input end to achieve the launch condition specified. Focus the near-field image of the output end, and centre it on the camera, either through automated means, or by using the monitor through manual means. Adjust the core and cladding illuminators to achieve optimal signal-to-noise while avoiding pixel saturation.

Record the digitized video data from the image as an array of pixel intensities I. The spacing parameters for the X and Y axes, δ_Y and δ_Y are equivalent to the magnification calibrations parameters, S_X and S_Y, respectively.

B.4.2.2 Measurement by the mechanical scan technique

B.4.2.2.1 One-dimension scan

Prepare, secure and align the specimen as indicated above. Adjust the output end to permit the magnified image to be scanned – this may involve focusing the image of the output end on the plane of the scanning aperture and centring the image so that the core's centre is at the expected position. Adjust the illuminator(s) to achieve optimal signal-to-noise. Often, mechanical scanning is employed to determine category A1 fibre core geometry only. In this case, only a core illuminator is used – the cladding is not illuminated.

Scan the near-field image, and record the intensities, I, and their associated positions, x.

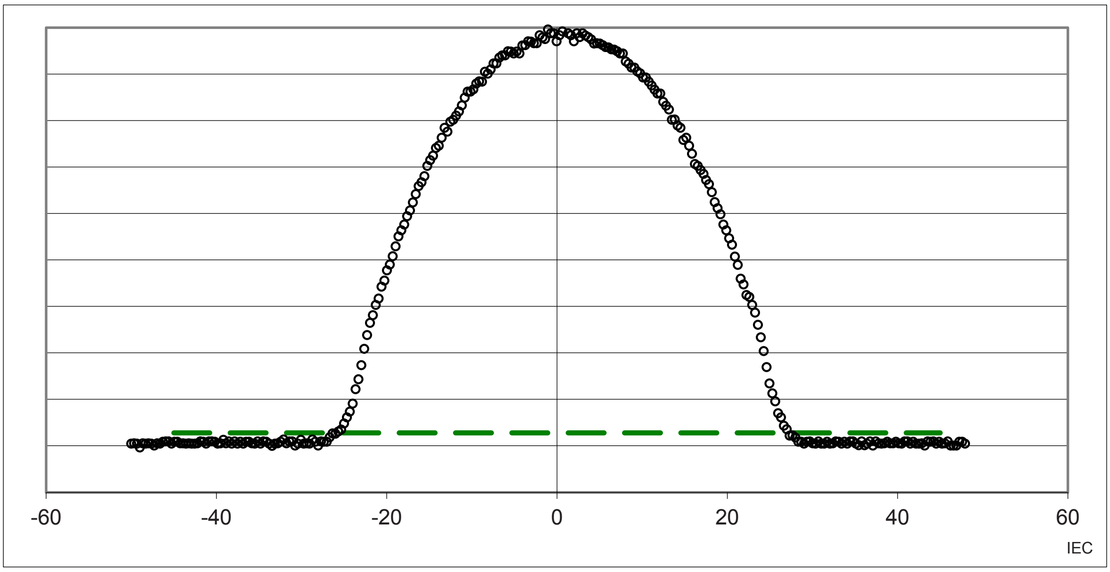


Figure B.3 – Typical 1-D near-field scan, category A1 core

B.4.2.2.2 Combinations of one-dimension scans at a set of angles

Acquire scans as described in B.4.2.2.1 at multiple angles, φ. Ensure that the scans share a common origin. For scans of a multimode core or scans including the cladding, each scan should pass through the core's (or cladding's) centre, which may mean re-aligning the scanner at each orientation.

B.4.2.2.3 Raster scanning

Acquire scans as described in B.4.2.2.1 at a set of lines perpendicular to the axis scanned in B.4.2.2.1 at raster positions recorded in y. The covered raster distance should be the same as the covered scan distance.

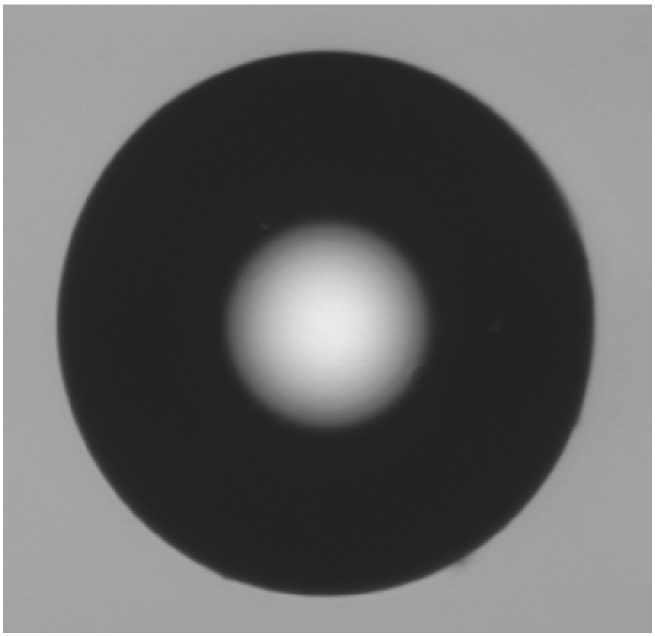


Figure B.4 – Typical raster near-field data, category A1 fibre

B.5 Calculations

Refer to Annexes C, D and E to reduce the near-field intensity data to geometry.

B.6 Results

In addition to the results listed in Clause 11, and depending on the specification requirements, the following information shall be provided on request:

- detector type and aperture size (single near-field scan technique only).

Annex C
(normative)

Edge detection and edge table construction

C.1 Introductory remarks

The determination of the boundary of delineation (edge detection) of a body is a fundamental transformation of RNF or TNF data toward determination of the body's geometry. Further transformations of these boundaries determine the geometry, including simple differences (diameter) and averaging (centre) of two diametrically opposed edges, or by fitting ellipses to sets of edges, as described in Annex D. Class A, B and C optical fibres have two bodies: the core and the cladding. The edge detection techniques described in this annex assume these bodies are approximately circular and nearly concentric.

The core boundary shall be determined by the decision-level technique (described in Clause C.2) for all fibre categories. The core boundary decision-level value is specified for all class A multimode fibres, but is not specified for class B and C single-mode fibres. (A recommended value for class B and C fibres is given below.) The cladding boundary may also be determined using the decision-level technique, but other techniques are allowed (these techniques often employ various kinds of spatial fiters and can act in one or two dimensions; these techniques are not described by this standard.) Note that for the video gray-scale RNF technique, as described in Annex B, it is required that whatever edge detection technique is used to determine the cladding boundary is the same technique used to calibrate the cladding diameter against a known diameter artefact.

C.2 Boundary detection by decision level

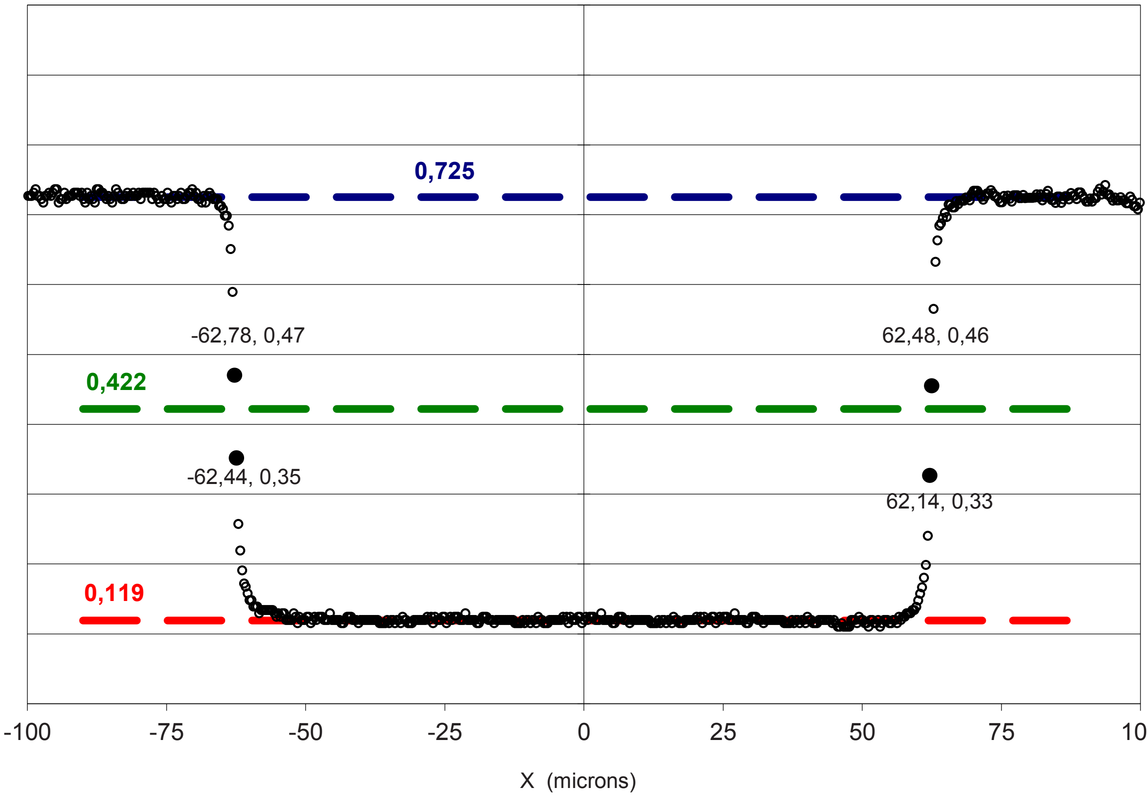
C.2.1 General approach

The decision-level boundary detection technique locates a boundary by finding a point in a data set which straddles a trigger intensity level, T. T is determined from a baseline intensity, I_{Base}, a peak intensity, I_{Max} and a fractional parameter, the decision factor K. The boundary is then defined as the interpolation of two points, x_{L} and x_{R}, that straddle T.

$$\begin{gathered} T = I_{\mathrm{Base}} + K\left(I_{\mathrm{Max}} - I_{\mathrm{Base}}\right) \\ x = x_{\mathrm{L}} + \left(x_{\mathrm{R}} - x_{\mathrm{L}}\right)\frac{\left(T - I_{\mathrm{L}}\right)}{\left(I_{\mathrm{R}} - I_{\mathrm{L}}\right)} \end{gathered} \tag{C.1}$$

In Figure C.1 below, a typical one-dimensional near-field intensity is shown. In this example the cladding casts a shadow on a bright background, and the core is un-illuminated. The red line shows the baseline intensity level, the blue line shows the peak reference level, and the green line shows the decision level (using a K of 0,5, or 50 %). The cladding crosses the threshold on the left and right hand sides of the x-axis. The fibre's diameter is the difference between these two crossings.

$$
\begin{aligned}
x_- &= -62,78 + (-62,44 + 62,78)\frac{0,422 - 0,47}{0,35 - 0,47} \\
&= -62,64 \\
x_+ &= 62,14 + (62,48 - 62,14)\frac{0,422 - 0,33}{0,46 - 0,33} \\
&= +62,38 \\
D &= (62,38 - (-62,64)) = 125,02
\end{aligned}
\qquad (C.2)
$$

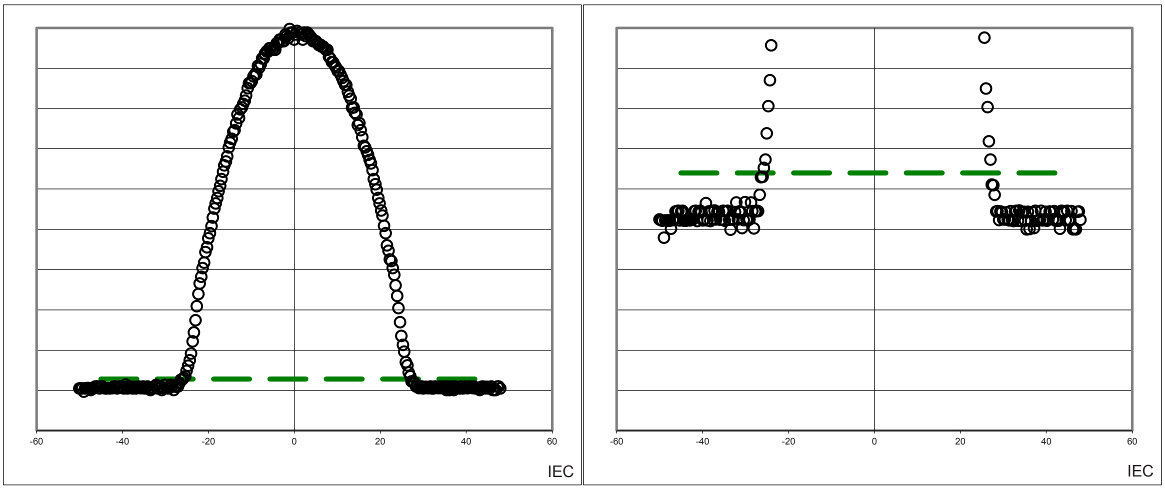


IEC

Figure C.1 – Typical one-dimensional data set, cladding only

C.2.2 Class A multimode fibre core reference level and *k* factor

In the example given in C.2.1, the reference levels were given. Estimation of reference levels can be crucial to valid determination of the boundary of a body, since the reference levels are used to determine the decision level. Cladding body boundaries have edge transitions that are steep, so small differences in the decision level will not greatly affect the location of a detected edge. However, as illustrated in Figure C.2, multimode core diameter is often defined using decision factors which locate features near the core boundary where the transition is shallow. Since these edge transitions are not sharp, small changes in reference levels can affect the location of the edge which will affect the final computed core diameter.



NOTE Right-hand graph is expanded in *Y* by 10.

Figure C.2 – Typical graded index core profile

The upper reference level of the core of graded-index fibres is taken as the highest intensity datum in the core region, or a reasonable average of data around the peak. Step-index multimode fibre core diameters use an upper reference level which needs to be determined in a fashion like the baseline since the signal inside the core may not be perfectly flat; take care to establish a reasonable upper reference level for these fibres.

In general, care should be taken to find repeatable and realistic baseline reference levels. For some transmitted near-field systems, for example one using a modulated core illuminator and demodulated signal, the baseline reference level is expected to be zero. For other systems, the baseline reference will not be zero and will need to be determined from the data set.

The default reference k-factor used for core diameter measurement of category A1 and A4 fibres is to be 0,025 (2,5 %), for category A2 and A3 fibres 0,5 (50 %) shall be used.

At the time of writing, all class A fibre specifications were being revised, partially to include the k-factor used to determine core geometry. Once these specifications are published including this information, the preceding paragraph shall be ignored and the information in the product specification be used in its place.

For day-to-day measurements, other values of k (other other core processing approaches) may be used – in these cases these non-reference measured values shall be mapped to the reference value for k (and method) as described in Annex F.

C.2.3 Class B and C single-mode fibres

Since the core edge table for single-mode fibres is only used to locate the core centre to compute concentricity error, the edge detection methodology is not critical. It is reasonable to use the maximum pixel in the core region as the upper reference level. Refer to C.2.2 to determine the baseline reference level, but note that errors in the baseline level are generally less important for these fibre classes. A k factor of 0,25 (25 %) is commonly employed.

C.2.4 Direct geometry computation of one-dimensional data

For a single-scan one-dimensionaldata set, once edge detection is complete, the body’s diameter can be computed as the simple difference between the edge detected on the right side of the scan and the edge detected of the left side of the scan.

If both the core and cladding bodies are detected, then an estimate of the concentricity can be made. The centre of the cladding or core is simply the average of its left and right edges. The concentricity estimate is simply the difference between the two centres.

Note that if scans are made at more than one angle, geometry can be computed for each angle as above. However, if three or more angular scans are available, it is recommended that their edges be assembled into an edge table as described in Clause C.3 and fit to an ellipse as described in Annex D.

C.3 Assembling edge tables from raw data

C.3.1 General

An edge table is defined as a list of X,Y data pairs whose entries constitute the bounding points of a body. Edge tables are composed of detected edges (using the decision-level method described above, or for the cladding, and appropriate filter) and describes a nearly circular closed curve over 360 °. Edge tables are extracted from two-dimensional raw intensity data of either refracted or transmitted near-field data as described in Annexes A and B. Edge tables can be assembled either from raster data sets or from multiple single scans taken at different angles. Each process is described below.

C.3.2 Edge tables from raster data

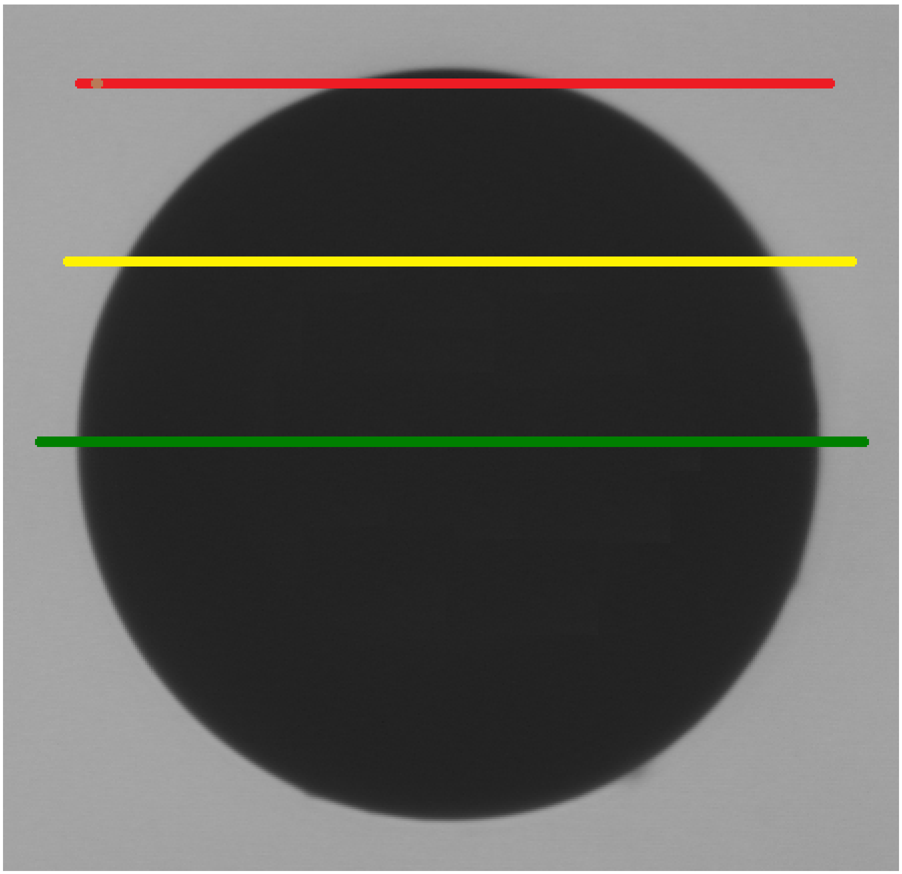


Figure C.3 – Raster data, cladding only

Figure C.3 shows a typical raster scan from a video near-field instrument showing a dark cladding against a bright background without the core illuminated. To construct a cladding edge table for this example, the image is inspected essentially pixel by pixel using the edge detection techniques discussed in Clause C.2, and a list constructed of the locations (X,Y) of detected edges.

Each row and column in the image may have two detectable edges (if the core were illuminated, then a subset of the rows and columns would have four detectable edges). The rows outside the fibre area contain no edges (nor do the columns outside the fibre). The green line shows a row near a diameter of the cladding. The red line highlights a row that scans nearly tangential to the cladding. Scans that pass near the centre of the cladding will have the sharpest edges, whilst tangential scans will produce very weak, hard-to-detect edges. It is therefore desirable to detect edges on rows or columns which pass as close as possible to the centre.

One approach to edge-detection in this image is to detect edges only on rows that pass near the centre, and to switch to column-wise edge detection for the remainder of the periphery. Generally, the best trade-off is to make this transition at the 45 ° and 135 ° angles on the image. The yellow line indicates the transition point where detection should switch from row-wise to column-wise.

Another approach is to only perform edge detection on scans which pass through the rough centre of the body. To use the entire image, two-dimensional interpolation can be employed to construct synthetic one-dimensional scans at a set of angles fine enough to capture the video resolution: the angular increment employed produces an arc length equal to the pixel spacing at the body's radius. The detected edges from each synthetic scan are then transformed onto the zero-angle coordinate system and added to the edge table.

When complete, a n_e length table of X_i, Y_i edges will be determined for each body analysed.

C.3.3 Edge tables from multi-angular one-dimensional scans

To assemble an edge table from a multi-angle scan set, process each scan as outlined in Clause C.2. It is important that each detected edge's location be referenced to a centre that is the point of rotation of the fibre. At the end, each body detected will have an associated list of length n_φ of $R_\mathrm{k},\varphi_\mathrm{k}$ pairs. The R data are detected edges for the body, both from the left and right sides of a scan. At this point, the R data are signed numbers; the left side edges will be negative (to the left of the rotation centre.) Next, transform the $R_\mathrm{k},\varphi_\mathrm{k}$ pairs into the Cartesian coordinate X,Y edge table.

$$\begin{aligned} X_\mathrm{k} &= R_\mathrm{k}\cos\varphi_\mathrm{k} \\ Y_\mathrm{k} &= R_\mathrm{k}\sin\varphi_\mathrm{k} \end{aligned} \qquad \text{(C.3)}$$

Annex D
(normative)

Edge table ellipse fitting and filtering

D.1 Introductory remarks

The general for fitting an ellipse to an edge table is given below. Both the core and cladding edge tables are fit to ellipses whose parameters are then used to compute the fibre's geometry.

D.2 General mathematical expressions for ellipse fitting

A general form for an ellipse is given as

$$0=\left[1-\frac{(x-x_0)^2}{A^2}+\frac{(x-x_0)(y-y_0)}{B^2}+\frac{(y-y_0)^2}{C^2}\right] \tag{D.1}$$

Expansion and substitution gives

$$0=ax^2+2bxy+cy^2+2dx+2fy+g \tag{D.2}$$

where

$$\begin{aligned} x_0&=\frac{cd-bf}{b^2-ac}\\ y_0&=\frac{af-bd}{b^2-ac}\\ A&=\frac{1}{\sqrt{-a}}\\ B&=-\frac{1}{\sqrt{-c}}\\ C&=-\frac{1}{\sqrt{-2b}} \end{aligned} \tag{D.3}$$

The rotation of the ellipse, φ is given by

$$\varphi=\frac{1}{2}\cot^{-1}\left(\frac{c-a}{2b}\right) \tag{D.4}$$

The major and minor radial dimensions of the ellipse are computed by

$$
\begin{aligned}
R_{\text{Major}} &= \sqrt{\frac{2(af^2 + cd^2 + gb^2 - 2bdf - acg)}{(b^2 - ac)\left[(c-a)\sqrt{1 + \dfrac{4b^2}{(a-c)^2}} - (c+a)\right]}} \\
R_{\text{Minor}} &= \sqrt{\frac{2(af^2 + cd^2 + gb^2 - 2bdf - acg)}{(b^2 - ac)\left[(a-c)\sqrt{1 + \dfrac{4b^2}{(a-c)^2}} - (c+a)\right]}}
\end{aligned}
\qquad \text{(D.5)}
$$

The ellipse can be expressed parametrically as

$$
\begin{aligned}
x' &= R_{\text{Major}}\cos(\theta)\cos(\varphi) - R_{\text{Minor}}\sin(\theta)\sin(\varphi) + x_0 \\
y' &= R_{\text{Major}}\cos(\theta)\sin(\varphi) + R_{\text{Minor}}\sin(\theta)\cos(\varphi) + y_0
\end{aligned}
\qquad \text{(D.6)}
$$

or, in cylindrical coordinates as

$$
r(\theta) = \sqrt{\frac{R_{\text{Major}}^{\;2}}{1 + \left(\dfrac{R_{\text{Major}}^{\;2}}{R_{\text{Minor}}^{\;2}} - 1\right)\sin^2(\theta - \varphi)}} \qquad \text{(D.7)}
$$

To fit the pixel data one solves the following linear system:

$$
\begin{pmatrix}
\sum X^4 & \sum X^3Y & \sum X^2Y^2 & \sum X^3 & \sum X^2Y & \sum X^2 \\
\sum X^3Y & \sum X^2Y^2 & \sum XY^3 & \sum X^2Y & \sum XY^2 & \sum XY \\
\sum X^2Y^2 & \sum XY^3 & \sum Y^4 & \sum XY^2 & \sum Y^3 & \sum Y^2 \\
\sum X^3 & \sum X^2Y & \sum XY^2 & \sum X^2 & \sum XY & \sum X \\
\sum X^2Y & \sum XY^2 & \sum Y^3 & \sum XY & \sum Y^2 & \sum Y \\
\sum X^2 & \sum XY & \sum Y^2 & \sum X & \sum Y & n_e
\end{pmatrix}
\begin{pmatrix} a \\ 2b \\ c \\ 2d \\ 2f \\ g \end{pmatrix}
=
\begin{pmatrix} \sum X^2 \\ \sum XY \\ \sum Y^2 \\ \sum X \\ \sum Y \\ n_e \end{pmatrix}
\qquad \text{(D.8)}
$$

Each summation above is computed using the n_{e} data pairs of X, Y points in the edge table.

NOTE The numerical precision of practical computers can affect the results. The principle contribution to precision-limited errors results from taking small differences of large yet similar numbers. In the system described above, the major cause of numerical precision problems is in using data pairs whose relative origin is outside the boundary of the body being fitted. For example, if the origin of the cladding edge table is taken as the lower left hand corner of the image, the $\times$ and y data set will be all positive. To avoid these errors, subtract from each x,y datum a rough centre somewhere inside the body.

D.3 Edge table filtering

Active filtering, or removal of raw edge points that represent cleave damage (or other flaws like dirt) from the set of fitted edges is allowed. An example of edge filtering is given below:

- For each edge in the edge table
  a) after fitting, compute the distance, d, between each edge in the fitted set and ellipse using Equation (C.8),

b) if d is greater than T micrometres, remove the edge from the edge table, and increment a counter of rejected edges, N_{bad},

c) If N_{bad} is greater than 1 % of the edges in the edge table, refit using the remaining edges.

– Repeat the above steps until step c) is false.

D.4 Geometric parameter extraction

In this clause, the subscripts "cl" and "co" differentiate the elliptical fit parameters of the cladding and core bodies.

Usinge the fitted ellipses, the following geometric parameters can be extracted:

X_{co},Y_{co} (μm):	fitted core centre
$R_{\mathrm{Major\ co}}$ (μm):	major radius of the core
$R_{\mathrm{Minor\ co}}$ (μm):	minor radius of the core
Core diameter (μm):	$(R_{\mathrm{Major\ CO}}+R_{\mathrm{Minor\ CO}})$
Core non-circularity (%):	200 $(R_{\mathrm{Major\ co}} - R_{\mathrm{Minor\ co}})$/Core diameter
X_{cl},Y_{cl} (μm):	fitted cladding centre
$R_{\mathrm{Major\ cl}}$ (μm):	major radius of the cladding
$R_{\mathrm{Minor\ cl}}$ (μm):	minor radius of the cladding
Cladding diameter (μm):	$(R_{\mathrm{Major\ CL}}+R_{\mathrm{Minor\ CL}})$
Cladding non-circularity (%):	200 $(R_{\mathrm{Major\ cl}} - R_{\mathrm{Minor\ cl}})$/Cladding diameter
Core/cladding concentricity error (μm):	$\left[(X_{\mathrm{cl}} - X_{\mathrm{co}})^2 + (Y_{\mathrm{cl}} - Y_{\mathrm{co}})^2\right]^{½}$

Annex E
(informative)

Fitting category A1 core near-field data to a power law model

E.1 Introductory remarks

Annex E describes the methodology to fit a power law profile to a raw near-field data set of a category A1 fibre core. Both transmitted and refracted near-field data can be processed using this approach. Core diameter, core centre (with limitations), and α, the power-law exponent, can be determined with this fitting technique. Pre-processing steps are generally required to successfully perform this fit. Clause E.2 identifies these pre-processing steps. Clause E.3 describes the fitting methodology in detail.

E.2 Preconditioning data for fitting

E.2.1 Motivation

The fitting process described in Clause E.3 requires a data set which satisfies two conditions: the data set is one-sided (only exists in positive radius) and, has a zero intensity baseline (zero intensity outside the core region). Two-dimensional data from Annex A, raster scanning, and Annex B, grey-scale technique can be pre-processed in similar ways as described in E.2.2. One-dimensional data from Method A or Method B share pre-processing requirements as described in E.2.3.

E.2.2 Transformation of a two-dimensional image to one-dimensional radial near-field

E.2.2.1 When to use

Use this processing method to convert a two-dimensional image of a category A1 fibre core to a one-dimensional data set which can then be fit to the power law profile as described in Clause E.3. Typically, these images will be gray-scale video images acquired using the transmitted near-field grey-scale method described in Annex B. Raster images taken using the refracted near-field method of Annex A can also be processed with this method.

E.2.2.2 Area of interest (optional)

Often, the initial raster or image will contain areas outside the core. These areas include the surrounding cladding and illumination field for a gray-scale image. When reducing the image to the one-dimensional near-field profile, these other areas can bias the fitting process described in Clause E.3. It is therefore useful to extract from the raw image a square area surrounding the core which the remainder of the algorithm will use. Since the baseline subtraction required in Clause E.3 uses information 1,2 times the nominal radial dimension of the core, extracting and using only this area is recommended. This extracted image will then be the image to be processed.

Of course, if an area of interest image is extracted from the original image, N_{Row}, N_{Col} and I will change. This subtlety is ignored for brevity’s sake for the remainder of this annex.

E.2.2.3 Centroid

Using the image, the near-field centre is computed by finding the centre of gravity of each Cartesian axis independently. To find the centroid, first find P_{Max} and P_{Min} respectively the intensities of the brightest and dimmest valid pixels in the entire centroid image and then compute the threshold T.

$$T = 0{,}1\left(P_{\mathrm{Max}} - P_{\mathrm{Min}}\right) + P_{\mathrm{Min}} \tag{E.1}$$

Next, compute the following three summations over all pixels, excluding pixels with intensities less than T, over the row and column indices r and c:

$$\begin{aligned}
S_{\mathrm{p}} &= \sum_{r=1}^{N_{\mathrm{Row}}} \sum_{c=1}^{N_{\mathrm{Col}}} \begin{cases} 0 & I_{\mathrm{r,c}} < T \\ I_{\mathrm{r,c}} & I_{\mathrm{r,c}} \geq T \end{cases} \\
S_{\mathrm{r}} &= \sum_{r=1}^{N_{\mathrm{Row}}} \sum_{c=1}^{N_{\mathrm{Col}}} \begin{cases} 0 & I_{\mathrm{r,c}} < T \\ rI_{\mathrm{r,c}} & I_{\mathrm{r,c}} \geq T \end{cases} \\
S_{\mathrm{c}} &= \sum_{r=1}^{N_{\mathrm{Row}}} \sum_{c=1}^{N_{\mathrm{Col}}} \begin{cases} 0 & I_{\mathrm{r,c}} < T \\ cI_{\mathrm{r,c}} & I_{\mathrm{r,c}} \geq T \end{cases}
\end{aligned} \tag{E.2}$$

Finally, compute the centroid, X_0, Y_0

$$\begin{aligned}
X_0 &= \frac{S_{\mathrm{c}}}{S_{\mathrm{P}}} \\
Y_0 &= \frac{S_{\mathrm{r}}}{S_{\mathrm{P}}}
\end{aligned} \tag{E.3}$$

NOTE If P_{Min} is significant when compared to P_{Max} (i.e. when the cladding is illuminated) then the centroid can be biased if the core image is not centred on the overall image. In these cases, the centroid estimation will be improved if P_{Min} (or some other estimate of the baseline or pedestal on which the core image sits) is subtracted from the image before centroid calculation.

E.2.2.4 Computation of radial data functions

This computation step reduces the 2-D pixel data into a 1-D radial function by averaging the pixels in sets of nested and overlapping annular rings (centred on X_0,Y_0) of thickness $2W$ (where W is 0,2 mm unless otherwise specified) centred on the optical centre of the fibre, X_0,Y_0, as defined in E.2.2.3. The spacing of the rings is W micrometres, although the ring's radial coordinate in the resulting radial data functions will be the radial centroid of the radial coordinates of the pixels in the ring.

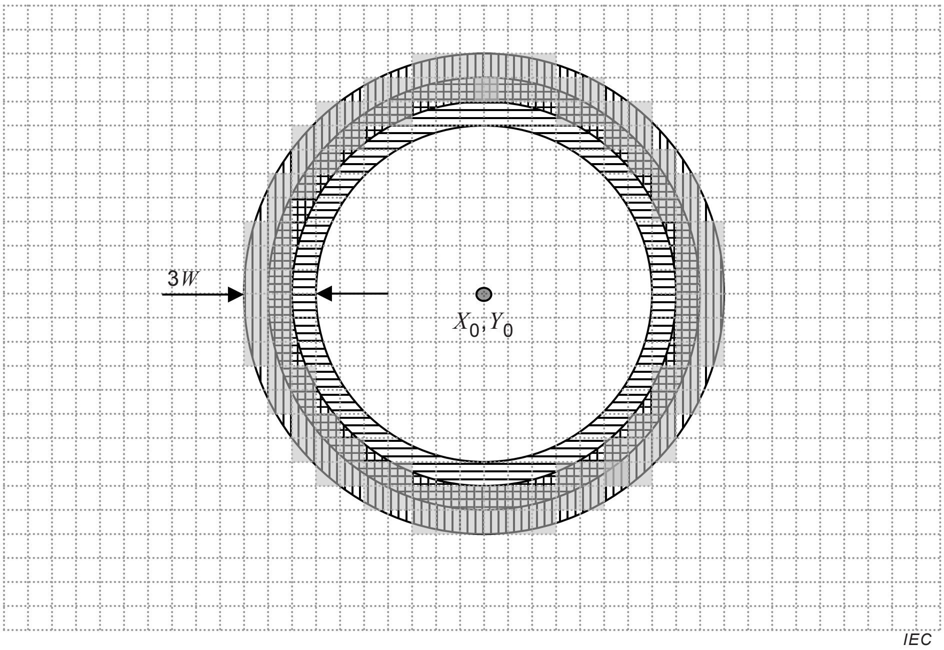


Figure E.1 – Filtering concept

In Figure E.1, the filtering concept is illustrated. The elements of the square grid are the pixels of the image. Two rings, centred on the optical centre X_0,Y_0, are shown: the outer ring is hatched vertically and the inner ring is hatched horizontally. Each ring has a width $2W$, and overlap in a region W wide. The overlap region in the diagram is cross-hatched. The grayed-in pixels are the pixels which will be averaged into the outer ring, since their centres fall inside the outer ring's boundary.

Use the following steps to compute the radial functions:

a) Determine the maximum radius of a complete ring. This step finds the largest ring that will fit in the image without being truncated by an image boundary. Compute the shortest distance to the edge of the image from the image centre

$$\begin{aligned} D_\mathrm{L} &= S_\mathrm{X} X_0 \\ D_\mathrm{R} &= S_\mathrm{X}(N_\mathrm{C} - X_0) \\ D_\mathrm{T} &= S_\mathrm{Y} Y_0 \\ D_\mathrm{B} &= S_\mathrm{Y}(N_\mathrm{R} - Y_0) \\ D &= \min(D_\mathrm{L}, D_\mathrm{R}, D_\mathrm{T}, D_B) \end{aligned} \tag{E.4}$$

where "min" finds the minimum of the four distances. Next, compute the number of rings, N_R, as

$$N_\mathrm{R} = \frac{D - W}{W} \tag{E.5}$$

a) Allocate and zero the three summation arrays, $S_\mathrm{R}(0..N_\mathrm{R})$, $S_\mathrm{I}(0..N_\mathrm{R})$, and $S_\mathrm{N}(0..\ N_\mathrm{R})$

For each and every pixel (on row r and column c), perform the following steps:

b) Compute the radial coordinate:

$$R = \sqrt{S_{\mathrm{Y}}^2 (r - Y_0)^2 + S_{\mathrm{X}}^2 (c - X_0)^2} \tag{E.6}$$

c) Compute the ring index i

$$i = trunc\left(\frac{R}{W}\right) + 1 \tag{E.7}$$

d) If i is less than or equal to N_{R} then sum into both ring i and ring i-1

$$\begin{aligned} S_{\mathrm{R}}(i) &= S_{\mathrm{R}}(i) + R \\ S_{\mathrm{I}}(i) &= S_{\mathrm{I}}(i) + I(r,c) \\ S_{\mathrm{N}}(i) &= S_{\mathrm{N}}(i) + 1 \end{aligned} \tag{E.8}$$

$$\begin{aligned} S_{\mathrm{R}}(i-1) &= S_{\mathrm{R}}(i-1) + R \\ S_{\mathrm{I}}(i-1) &= S_{\mathrm{I}}(i-1) + I(r,c) \\ S_{\mathrm{N}}(i-1) &= S_{\mathrm{N}}(i-1) + 1 \end{aligned} \tag{E.9}$$

The above double sum implements the overlapping-ring smoother.

e) Finally, compute the parametric function pair (where i is the parameter) for each ring by computing the average radius and average intensity in each ring:

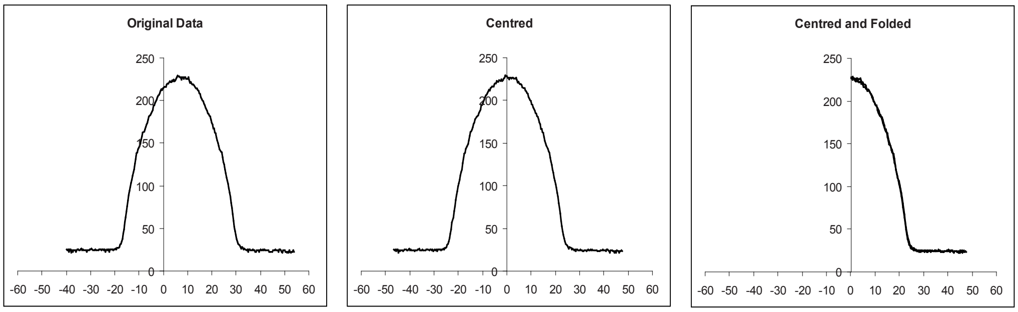
$$\begin{aligned} R(i) &= \frac{S_{\mathrm{R}}(i)}{S_{\mathrm{N}}(i)} \\ NF'(i) &= \frac{S_{\mathrm{I}}(i)}{S_{\mathrm{N}}(i)} \end{aligned} \tag{E.10}$$

Depending on the camera’s resolution and the ring thickness selected, it is possible for some of the interior rings to contain no pixels, and so the corresponding S_{N} values will be zero. In this case, the ring should be omitted and the subsequent array elements shifted up, and N_{R} should be decremented. It is also possible for two or more adjacent rings to have the same $\bar{R}$ (or trivially identical, say within 0,01 mm) – in these cases the radii and intensities in these adjacent rings should be averaged, and those rings replaced with one ring of averaged $\bar{R}$ and averaged intensity, and N_{R} should be decremented appropriately.

E.2.3 Pre-processing of one-dimensional near-field data

E.2.3.1 General

One-dimensional near-field category A1 fibre core data can be measured as a single line scan using the refracted near-field method, the mechanical scanning transmitted near-field method, or as individual video lines from the grey-scale transmitted near-field method. Generally, data of this form have a left and right hand side, i.e. in the line there is intensity data a negative radius and positive radius. The fitting process described in Clause E.3 can only use positive radii, and so the centre of the data shall be found to determine where R = 0. Once the centre is known, the radial positions can be re-centred. Then, either the data has to be folded around the centre (moving the left side data to the right by reflection), or one side of the data should be extracted from the set to be processed alone. Generally, folding the data is preferred.


Original Data

Centred

Centred and Folded

IEC

Figure E.2 – Illustration of 1-D near-field preconditioning, typical video line

The input data are N pairs R'_i, I'_i.

E.2.3.2 Centre determination

Using the image, the near-field centre is computed by finding the centre of gravity of the measured profile in radius. To find the centroid, first find P_{Max} and P_{Min} respectively the largest and smallest intensities in the measured profile, and then compute the threshold T:

$$T = 0{,}1\,(P_{\text{Max}} - P_{\text{Min}}) + P_{\text{Min}} \tag{E.11}$$

Next, compute the following summations over the entire profile, excluding profile data with intensities less than T:

$$\begin{aligned} S &= \sum_{i=1}^{N} \begin{cases} 0 & I_{1-D_i} < T \\ I_{1-D_i} & I_{1-D_i} \geq T \end{cases} \\ SR &= \sum_{i=1}^{N} \begin{cases} 0 & I_{1-D_i} < T \\ iI_{1-D_i} & I_{1-D_i} \geq T \end{cases} \end{aligned} \tag{E.12}$$

Finally, compute the centroid,

$$R_0 = \frac{SR}{S} \tag{E.13}$$

NOTE If P_{Min} is significant when compared to P_{Max} (i.e. when the cladding is illuminated) then the centroid can be biased if the core image is not centred on the overall image. In these cases, the centroid estimation will be improved if P_{Min} (or some other estimate of the baseline or pedestal on which the core image sits) is subtracted from the image before centroid calculation.

E.2.3.3 Folding the profile

Once the centre is known, folding the profile is trivial:

$$R_i = \left| R'_i - R_0 \right| \tag{E.14}$$

where the vertical bars denote the absolute value. Once the data is folded, it is convenient to sort the data set in increasing R so as to not complicate the remainder of the fitting algorithm.

E.2.4 Baseline subtraction

Usually, once the radial functions have been computed, the N_F' function outside of the core region will have a non-zero value, herein referred to as the baseline, or B. This baseline value, B, can be attributed to video dark signal, cladding illumination, a non-zero cladding refractive index or other causes. To properly condition the data to prepare for fitting as described in Clause D.3, this baseline shall be subtracted. One approach is to compute B as the average of $N_F´$ over the radial range from 0,575 times the fibre's nominal core diameter, to 0,6 times the nominal core diameter.

Subtract the baseline from T:

$$I_i = I_i' - B \quad 0 \le i \le N_R \tag{E.15}$$

There are cases where B is expected to be zero: for example, when a chop-in amplifier is used to demodulate a modulated signal from a one-dimensional mechanical near-field scan. In these cases it is allowable to take B as zero.

E.3 Fitting a power-law function to an category A1 fibre near-field profile

The conditioned near-field data from Clause E.2 is fit to the following power-law model:

$$IF(r) = I_0\left[1 - \left(\frac{r}{a}\right)^{\alpha}\right] \tag{E.16}$$

where I_0 is the maximum intensity according to the best-fit model, α is the power law shape factor, and a is the best fit core radius. This model shall be fit to the R and I data set using the least squares criteria by minimizing S:

$$S = \sum_{i=i_{10}}^{i_{80}}\left[I_i - I_0\left[1 - \left(\frac{R_i}{a}\right)^{\alpha}\right]\right]^2 \tag{E.17}$$

where i_{10} and i_{80} are the indices that bracket the data set where I lies between 10 % and 80 % of the maximum of I, respectively. The reason to limit the fit region is two-fold: first, the 80 % limit excludes near-core-centre anomalies; second, the 10 % limit excludes the tail of these profiles, which do not conform well to the model due to diffusion and intentional design features.

To use Equation (E.17) as written, the data set should be established by in increasing R and ignore any data very near the core which falls below the 80 % limit.

Minimizing S in Equation (E.17) requires non-linear equation solving techniques, however it is important to notice that the fit parameters I_0, α and a are coupled. Conventional non-linear solvers will generally fail to find a solution for a given data set and so special techniques should be employed. First, combining terms, Equation (E.16) is recast as

$$\begin{gathered} IF(r) = I_0 + Kr^{\alpha} \\ where\ a = -K^{-\frac{1}{\alpha}} \end{gathered} \tag{E.18}$$

Equation (E.17) can be rewritten as

$$S = \sum_{i=i_{10}}^{i_{80}} \left[I_i - I_0 - Kr^{\alpha} \right]^2 \tag{E.19}$$

S is minimum when

$$\begin{aligned}
\frac{\partial S}{\partial I_0} &= 0 = 2nI_0 + 2K\sum r_i^{\alpha} - 2\sum I_i \\
\frac{\partial S}{\partial K} &= 0 = 2I_0\sum r_i^{\alpha} + 2K\sum r_i^{2\alpha} - 2\sum r_i^{\alpha} I_i \\
\frac{\partial S}{\partial \alpha} &= 0 = 2KI_0\sum \log(r_i) r_i^{\alpha} + 2K^2\sum \log(r_i) r_i^{2\alpha} - 2K\sum \log(r_i) r_i^{\alpha} I_i
\end{aligned} \tag{E.20}$$

Combining the first two derivatives and solving simultaneously for I_0 and K, we get

$$\begin{aligned}
K &= \frac{\sum I_i r^{\alpha} - \frac{\sum I_i \sum r^{\alpha}}{n}}{\sum r^{2\alpha} - \frac{\left(\sum r^{\alpha}\right)^2}{n}} \\
I_0 &= \frac{\sum I_i - K\sum r^{\alpha}}{n}
\end{aligned} \tag{E.21}$$

From Equation (E.21) it can be observed that for any α, both K and I_0 can be calculated directly. It is therefore possible to reduce the three-parameter nonlinear minimization of Equation (E.17) to a one-parameter minimization of Equation (E.19) by exploiting Equation (E.21). The process for solving the system is then simply to solve Equation (E.18) with a one-dimensional nonlinear solver (i.e. Newton's method) on α, with the kernel function using first Equation (E.21) to compute K and I_0 and returning Equation (E.19) as the function to be minimized.

Once the solution is found, the core diameter is found as twice a, which is computed from K, using Equation (E.18).

Annex F
(informative)

Mapping class A core diameter measurements

F.1 Introductory remarks

Annex B, in combination with Annexes C and D, describes the reference test method (RTM) to determine the core diameter for class A multimode fibre core diameter. The sample length for various categories and sub-categories of A fibre can extend into the hundreds of metres, and is specified in the detail specification for that category or class. For day-to-day measurements it is impractical to require the stress-free deployment of many metres of fibre to determine its core diameter and so it is desirable to allow shorter lengths (2 m) to be employed. Additionally, as a practical matter the methodology of Annex C to determine the curve of delineation of the core boundary may be impractical dependent on the design of the fibre when such short lengths are employed with overfilling launch conditions. To accommodate these difficulties, the mapping of the reference test condition may be mapped onto a more practical test condition.

If alternate measurement conditions are employed for daily production measurements, the alternate condition's core diameter can be transformed to estimate the reference condition diameter.

F.2 Mapping function

For a given fibre process and measurement regime, if it can be proven that a determination of a steady-state bias exists between the reference test method for determining class A fibre core diameter, including the reference length and analysis conditions and another method (for example employing a shorter test length and/or decision threshold or analysis technique), then a mapping function may be employed which transforms a core diameter measured using the alternative method to an approximation of the core diameter resulting from the reference method. It is allowable that these mapped diameters be reported as the core diameter. The mapping function can take any form.

An additive offset, Z:

$$CD_{\mathrm{Re}f} = CD_{\mathrm{Prod}} + Z \tag{F.1}$$

A multiplicative scaling factor, M:

$$CD_{\mathrm{Re}f} = M \times CD_{\mathrm{Prod}} \tag{F.2}$$

Or any other provably utile function, f:

$$CD_{\mathrm{Re}f} = f(CD_{\mathrm{Prod}}) \tag{F.3}$$

Bibliography

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