

INTERNATIONAL STANDARD



**Optical fibres –
Part 1-45: Measurement methods and test procedures – Mode field diameter**

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Part 1-45: Measurement methods and test procedures – Mode field diameter**

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CONTENTS

| | |
|--|----|
| FOREWORD..... | 5 |
| 1 Scope..... | 7 |
| 2 Normative references | 7 |
| 3 Terms, definitions and abbreviated terms | 7 |
| 3.1 Terms and definitions..... | 7 |
| 3.2 Abbreviated terms..... | 7 |
| 4 General consideration about mode field diameter | 8 |
| 5 Reference test method | 8 |
| 6 Apparatus..... | 8 |
| 6.1 General..... | 8 |
| 6.2 Light source | 9 |
| 6.3 Input optics | 9 |
| 6.4 Input positioner | 9 |
| 6.5 Cladding mode stripper | 9 |
| 6.6 High-order mode filter | 9 |
| 6.7 Output positioner | 9 |
| 6.8 Output optics | 10 |
| 6.9 Detector..... | 10 |
| 6.10 Computer..... | 10 |
| 7 Sampling and samples..... | 10 |
| 7.1 Sample length..... | 10 |
| 7.2 Sample end face..... | 10 |
| 8 Procedure..... | 10 |
| 9 Calculations..... | 10 |
| 9.1 Basic formulae | 10 |
| 9.2 Method A – Direct far-field scan | 10 |
| 9.3 Method B – Variable aperture in the far field | 11 |
| 9.4 Method C – Near-field scan..... | 12 |
| 10 Results | 13 |
| 10.1 Information available with each measurement..... | 13 |
| 10.2 Information available upon request | 13 |
| 11 Specification information | 13 |
| Annex A (normative) Requirements specific to method A – Mode field diameter by direct far-field scan | 14 |
| A.1 Apparatus | 14 |
| A.1.1 General | 14 |
| A.1.2 Scanning detector assembly – Signal detection electronics | 14 |
| A.1.3 Computer..... | 15 |
| A.2 Procedure | 15 |
| A.3 Calculations | 15 |
| A.3.1 Determine folded power curve | 15 |
| A.3.2 Compute the top (T) and bottom (B) integrals of Formula (1) | 15 |
| A.3.3 Complete the calculation | 16 |
| A.4 Sample data | 16 |
| Annex B (normative) Requirements specific to method B – Mode field diameter by variable aperture in the far field | 17 |

| | | |
|---|--|----|
| B.1 | Apparatus | 17 |
| B.1.1 | General | 17 |
| B.1.2 | Output variable aperture assembly | 17 |
| B.1.3 | Output optics system | 18 |
| B.1.4 | Detector assembly and signal detection electronics | 18 |
| B.2 | Procedure | 18 |
| B.3 | Calculations | 18 |
| B.3.1 | Determine complementary aperture function | 18 |
| B.3.2 | Complete the integration | 19 |
| B.3.3 | Complete the calculation | 19 |
| B.4 | Sample data | 19 |
| Annex C (normative) Requirements specific to method C – Mode field diameter by near-field scan | | 20 |
| C.1 | Apparatus | 20 |
| C.1.1 | General | 20 |
| C.1.2 | Magnifying output optics | 20 |
| C.1.3 | Scanning detector | 21 |
| C.1.4 | Detection electronics | 21 |
| C.2 | Procedure | 21 |
| C.3 | Calculations | 21 |
| C.3.1 | Calculate the centroid | 21 |
| C.3.2 | Fold the intensity profile | 22 |
| C.3.3 | Compute the integrals | 22 |
| C.3.4 | Complete the calculation | 23 |
| C.4 | Sample data | 23 |
| Annex D (normative) Requirements specific to method D – Mode field diameter by optical time domain reflectometer (OTDR) | | 24 |
| D.1 | General | 24 |
| D.2 | Apparatus | 24 |
| D.2.1 | OTDR | 24 |
| D.2.2 | Optional auxiliary switches | 24 |
| D.2.3 | Optional computer | 25 |
| D.2.4 | Test sample | 25 |
| D.2.5 | Reference sample | 25 |
| D.3 | Procedure – Orientation and notation | 25 |
| D.4 | Calculations | 26 |
| D.4.1 | Reference fibre mode field diameter | 26 |
| D.4.2 | Computation of the sample mode field diameter | 26 |
| D.4.3 | Validation | 27 |
| Annex E (informative) Sample data sets and calculated values | | 29 |
| E.1 | General | 29 |
| E.2 | Method A – Mode field diameter by direct far-field scan | 29 |
| E.3 | Method B – Mode field diameter by variable aperture in the far field | 30 |
| E.4 | Method C – Mode field diameter by near-field scan | 30 |
| Bibliography | | 31 |
| Figure 1 – Transform relationships between measurement results | | 8 |
| Figure A.1 – Far-field measurement set | | 14 |

Figure B.1 – Variable aperture by far-field measurement set..... 17

Figure C.1 – Near-field measurement set-ups 20

Figure D.1 – Optical switch arrangement 25

Figure D.2 – View from reference fibre A 26

Figure D.3 – View from reference fibre B 26

Figure D.4 – Validation example – Comparison of methods..... 27

Table 1 – Abbreviated terms 7

Table E.1 – Sample data, method A – Mode field diameter by direct far-field scan 29

Table E.2 – Sample data set, method B – Mode field diameter by variable aperture in the far field 30

Table E.3 – Sample data set, method C – Mode field diameter by near-field scan 30

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OPTICAL FIBRES –

Part 1-45: Measurement methods and test procedures – Mode field diameter

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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition IEC 60793-1-45:2017. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

IEC 60793-1-45 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 2017. This edition constitutes a technical revision.

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

- a) Modification of the minimum distance between the fibre end and the detector for the direct far field scan (Annex A).
- b) Generalization of the requirement for the minimum dynamic range for all fibre types (Annex A).

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

| Draft | Report on voting |
|--------------|------------------|
| 86A/2300/CDV | 86A/2366/RVC |

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.

A list of all parts in the IEC 60793 series, published under the general title *Optical fibres*, 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,
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OPTICAL FIBRES –

Part 1-45: Measurement methods and test procedures – Mode field diameter

1 Scope

This part of IEC 60793 establishes uniform requirements for measuring the mode field diameter (MFD) of single-mode optical fibre, thereby assisting in the inspection of fibres and cables for commercial purposes.

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 60793-1-40:2001, *Optical fibres – Part 1-40: Attenuation measurement methods* ~~and test procedures – Attenuation~~

~~IEC 60793-2, Optical fibres – Part 2: Product specifications – General~~

3 Terms, definitions and abbreviated terms

3.1 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>

3.2 Abbreviated terms

The abbreviated terms are given in Table 1.

Table 1 – Abbreviated terms

| Abbreviated term | Full term |
|------------------|-----------------------------------|
| CCD | charge-coupled devices |
| FWHM | full width half maximum |
| MFD | mode field diameter |
| OTDR | optical time domain reflectometer |
| RTM | reference test method |

4 General consideration about mode field diameter

The mode field diameter measurement represents a measure of the transverse extent of the electromagnetic field intensity of the guided mode in a fibre cross section, and it is defined from the far-field intensity distribution as a ratio of integrals known as the Petermann II definition. See Formula (1).

The definitions of mode field diameter are strictly related to the measurement configurations. The mathematical equivalence of these definitions results from transform relationships between measurement results obtained by different implementations summarized in Figure 1.

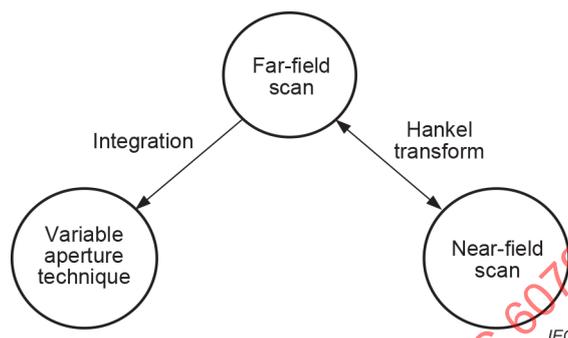


Figure 1 – Transform relationships between measurement results

Four methods are described for measuring mode field diameter:

- method A: direct far-field scan;
- method B: variable aperture in the far field;
- method C: near-field scan;
- method D: bi-directional backscatter using an optical time domain reflectometer (OTDR).

All four methods apply to all categories of type B single-mode fibre shown in IEC 60793-2 and operating near 1 310 nm or 1 550 nm. Method D is not recommended for the measurement of fibres of unknown type or design.

Information common to all four methods is contained in Clause 1 to Clause 11, and information pertaining to each individual method appears in Annex A, Annex B, Annex C, and Annex D respectively.

5 Reference test method

Method A, direct far-field scan, is the reference test method (RTM), which shall be the one used to settle disputes.

6 Apparatus

6.1 General

The following apparatus is common to all measurement methods. Annex A, Annex B, Annex C, and Annex D include layout drawings and other equipment requirements for each of the four methods, respectively.

6.2 Light source

For method A, method B and method C, use a suitable coherent or non-coherent light source, such as a semiconductor laser or a ~~sufficiently~~ powerful filtered white light source. ~~The source shall produce sufficient radiation at the intended wavelength(s) and be stable in intensity over a time period sufficient to perform the measurement.~~

A monochromator or interference filter(s) may be used, if required, for wavelength selection. The detail specification shall ~~specify~~ indicate the wavelength of the source. The full width half maximum (FWHM) spectral line width of the source shall ≤ 10 nm, unless otherwise specified.

The source power level shall be chosen so it is not impacting the repeatability of the mode diameter measurement.

The source power shall be stable for the complete duration of the measurement.

See Annex D for method D.

6.3 Input optics

For method A, method B, and method C, an optical lens system or fibre pigtail may be employed to excite the ~~specimen~~ sample. It is recommended that the power coupled into the ~~specimen~~ sample be relatively insensitive to the position of its input end face. This can be accomplished by using a launch beam that spatially and angularly overfills the input end face.

If using a butt splice, employ index-matching material between the fibre pigtail and the ~~specimen~~ sample to avoid interference effects. The coupling shall be stable for the duration of the measurement.

See Annex D for method D.

6.4 Input positioner

Provide means of positioning the input end of the ~~specimen~~ sample to the light source. Examples include the use of x-y-z micropositioner stages, or mechanical coupling devices such as connectors, vacuum splices, or three-rod splices. The position of the fibre shall remain stable over the duration of the measurement.

6.5 Cladding mode stripper

Use a device that extracts cladding modes. Under some circumstances, the fibre coating will perform this function.

6.6 High-order mode filter

Use a means to remove high-order propagating modes in the wavelength range that is greater than or equal to the cut-off wavelength of the ~~specimen~~ sample. For example, a one-turn bend with a radius of 30 mm on the fibre is generally sufficient for most ~~B1.1 to B6~~ B-652, B-653, B-654, B-655, B-656 and B-657 fibres. For some ~~B6~~ B-657 fibres, smaller radius, multiple bends, or longer ~~specimen~~ sample length can be applied to remove high-order propagating modes.

6.7 Output positioner

Provide a suitable means for aligning the fibre output end face to allow an accurate axial adjustment of the output end, such that, at the measurement wavelength, the scan pattern is suitably focused on the plane of the scanning detector. Such coupling may include the use of lenses or ~~may be~~ a mechanical connector to a detector pigtail.

Provide means such as a side-viewing microscope or camera with a crosshair to locate the fibre at a fixed distance from the apertures or detectors. It ~~may~~ can be sufficient to provide only longitudinal adjustment if the fibre is constrained in the lateral plane by a device such as a vacuum chuck (this depends mainly upon the size of the light detector).

6.8 Output optics

See the appropriate annex: Annex A, Annex B, Annex C or Annex D.

6.9 Detector

See the appropriate annex: Annex A, Annex B, Annex C or Annex D.

6.10 Computer

Use a computer to perform operations such as controlling the apparatus, taking intensity measurements, and processing the data to obtain the final results. For individual details, see the appropriate annex: Annex A, Annex B, Annex C or Annex D.

7 Sampling and ~~specimens~~ samples

7.1 ~~Specimen~~ Sample length

For method A, method B and method C, the ~~specimen~~ sample shall be a known length, typically $2\text{ m} \pm 0,2\text{ m}$ for most ~~B1-1 to B6~~ B-652, B-653, B-654, B-655, B-656 and B-657 fibres. For some ~~B6~~ B-657 fibres, longer ~~specimen~~ sample length can be used to avoid high-order propagating modes, 22 m for example.

For method D, OTDR, the sample shall be long enough to exceed (or be positioned beyond) the dead zone of the OTDR, with both ends accessible, as described in the backscatter test method in IEC 60793-1-40.

7.2 ~~Specimen~~ Sample end face

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

8 Procedure

See Annex A, Annex B, Annex C and Annex D for method A, method B, method C, and method D, respectively.

9 Calculations

9.1 Basic formulae

The basic formulae for calculating mode field diameter are Formula (1) for method A, Formula (2) for method B and Formula (6) for method C. For additional calculations, see the appropriate annex: Annex A, Annex B, Annex C or Annex D. Sample data sets for method A, method B and method C are included in Annex E.

9.2 Method A – Direct far-field scan

The following formula defines the mode field diameter for method A in terms of the electromagnetic field emitted from the end of the ~~specimen~~ sample.

Calculate the mode field diameter by scanning the far-field data and evaluating the Petermann II integral, which is defined from the far-field intensity distribution:

$$2W_0 = \frac{\lambda\sqrt{2}}{\pi} \left[\frac{\int_0^{\pi/2} P_F(\theta) \sin(\theta) \cos(\theta) d\theta}{\int_0^{\pi/2} P_F(\theta) \sin^3(\theta) \cos(\theta) d\theta} \right]^{1/2} \quad (1)$$

where

$2W_0$ is the mode field diameter in μm ;

$P_F(\theta)$ is the far-field intensity distribution;

λ is the wavelength of measurement in μm ;

θ is the angle in the far-field measurement from the axis of the fibre.

NOTE 1 The integration limits are shown to be from zero to $\pi/2$, but it is understood that the integrands approach zero with increasing argument so that, in practice, the integrals can be truncated.

NOTE 2 P_F is $F^2(\theta)$ in ITU-T documents.

The far-field method for obtaining the mode field diameter of a single-mode fibre is a two-step procedure. First, measure the far-field radiation pattern of the fibre. Second, use a mathematical procedure based on the Petermann II far-field definition to calculate the mode field from far-field data, as described in Formula (1).

Annex E provides sample data and calculated $2W_0$ values for verifying the numerical evaluation of the Petermann II Integral. The sample data are in the form of the folded power, $P_F(\theta)$, as a function of the angle, θ .

9.3 Method B – Variable aperture in the far field

Formula (2) defines the mode field diameter for method B in terms of the electromagnetic field emitted from the end of the specimen sample.

Calculate the mode field diameter, $2W_0$, as follows:

$$2W_0 = \left(\frac{\lambda}{\pi D} \right) \left[\int_0^{\infty} a(x) \frac{x}{(x^2 + D^2)^2} dx \right]^{-1/2} \quad (2)$$

where

$2W_0$ is the mode field diameter, in μm ;

λ is the wavelength of measurement, in μm ;

D is the distance between the aperture and the fibre, in mm;

$a(x)$ is the complementary aperture transmission function, calculated as

$$a(x) = 1 - \frac{P(x)}{P(\text{max})} \quad (3)$$

where

$P_{(x)}$ is the power measured through an aperture of radius, x , or half angle, θ ;

$P_{(max)}$ is the maximum power, assuming an infinite aperture;

x is the aperture radius, calculated as

$$x = D \tan(\theta) \tag{4}$$

Another equivalent expression of Formula (2) is

$$2W_0 = \frac{\lambda\sqrt{2}}{\pi} \left[\int_0^\infty a(\theta) \sin 2\theta d\theta \right]^{-1/2} \tag{5}$$

The variable aperture far-field method for obtaining the mode field diameter of a single-mode fibre is a two-step procedure. First, measure the two-dimensional far-field pattern as the power passing through a series of transmitting apertures of various size. Second, use a mathematical procedure to calculate the mode field diameter from the far-field data.

The mathematical basis for the calculation of mode field diameter is based on the Petermann II far-field definition from Formula (1). Formula (2) and Formula (5) can be derived from Formula (1) by integration.

9.4 Method C – Near-field scan

The following formula defines the mode field diameter for method C in terms of the electromagnetic field emitted from the end of the ~~specimen~~ sample.

Calculate the mode field diameter from the measured near-field intensity distribution, using the following integral:

$$2W_0 = 2 \left(\frac{\int_0^\infty r f^2(r) dr}{\int_0^\infty r \left(\frac{df(r)}{dr} \right)^2 dr} \right)^{1/2} \tag{6}$$

where

$2W_0$ is the mode field diameter, in μm ;

r is the radial coordinate, in μm ;

$f^2(r)$ is the near-field intensity distribution.

NOTE The upper integration limits are shown to infinity, but it is understood that since the integrands approach zero with increasing argument, in practice the integrals can be truncated. A smoothing algorithm can be used for the calculation of the derivative.

The near-field scan method for obtaining the mode field diameter of a single-mode fibre is a two-step procedure. First, measure the radial near-field pattern. Second, use a mathematical procedure to calculate the mode field diameter from the near-field data.

The mathematical basis for the calculation of the mode field diameter is based on the Petermann II definition from Formula (1). The near field, $f(r)$, and the far field, $F(\theta)$, form a Hankel transform pair. By Hankel transforming and using $P_F = F^2(\theta)$, it is possible to derive Formula (6) from Formula (1), and vice versa.

10 Results

10.1 Information available with each measurement

Report the following information with each measurement:

- date and title of measurement;
- identification of ~~specimen~~ sample;
- optical source wavelength;
- mode field diameter(s), in micrometres.

10.2 Information available upon request

The following information shall be available upon request:

- measurement method used: method A, method B, method C or method D;
- type of optical source used and its spectral width (FWHM);
- description of equipment;
- description of high-order modes filter;
- details of computation technique;
- date of latest calibration of measurement equipment.

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 – Mode field diameter by direct far-field scan

A.1 Apparatus

A.1.1 General

Annex A describes apparatus in addition to the requirements set down in Clause 6.

Figure A.1 illustrates a typical set-up for measurement by direct far-field scan.

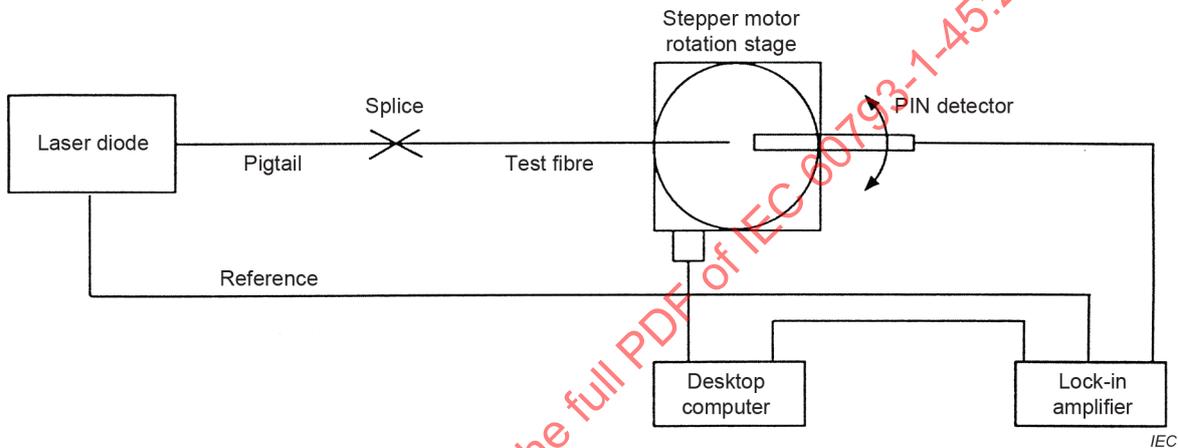


Figure A.1 – Far-field measurement set

A.1.2 Scanning detector assembly – Signal detection electronics

Use a mechanism to scan the far-field intensity distribution. Use a scanning device capable of 0,5° steps or finer to scan the detector. Use a means of aligning the fibre axis with respect to the rotation plane of the detector, and of aligning the fibre end-face with the centre of rotation of the scan. A typical system might include a PIN photodiode, operating in a photovoltaic mode, amplified by a current-input preamplifier, with synchronous detection by a lock-in amplifier. The detector should be at least 10 mm from the fibre end (to ensure the detector to scan the far field), and the detector's active area should not subtend an angle too large in the far field. ~~To ensure this, place the detector at a distance from the fibre end greater than $2wb/\lambda$, where $2w$ is the expected mode field diameter of the specimen and b is the diameter of the active area of the detector.~~

~~For very accurate measurements, the minimum dynamic range of the measurement should be 50 dB. This corresponds to a maximum scan half angle of 20° and 25°, or greater, for category B1 and B2 fibres, respectively. Reducing the dynamic range (or maximum scan half angle) requirements may introduce errors. For example, restricting those values to 30 dB and 12,5° for category B1 fibres, and to 40 dB and 20° for category B2 fibres, may result in a relative error, in the determination of the mode field diameter, that is greater than 1%.~~

To ensure this, place the detector at a distance d from the fibre end with $d = K \times \frac{2w \cdot b}{\lambda}$

where

$2w$ is the expected mode field diameter of the sample,

- b is the diameter of the active area of the detector,
- λ is the wavelength,
- K is the resolution factor which value is big enough to prevent the degradation of the far field scan and its impact on the calculation of the mode field diameter.

A value of K , greater than 20, is suitable for most fibre types and guarantees less than 0,1 % of error in the mode field diameter calculation.

For accurate measurements, the dynamic range of the measurement should be greater than 50 dB. The maximum scan half-angle depends on the fibre type and should be chosen so that the far field scan is characterized down to 50 dB of the maximum signal.

Reducing the dynamic range (or maximum scan half-angle) requirements can introduce errors.

A.1.3 Computer

A typical system should also include a computer to process the far-field data.

A.2 Procedure

Align the fibre in the system, prepared as described in Clause 6, with its output end aligned on the detector assembly for maximum power.

Scan the detector in $0,5^\circ$ steps, equally spaced, and record the detector power.

Calculate a value of the Petermann II integral from the recorded data and use it to compute the fibre mode field diameter as described in Formula (1), and in Clause A.3.

A.3 Calculations

A.3.1 Determine folded power curve

The folded power curve for $0 \leq \theta_i = \theta_{\max}$ is

$$P_F(\theta_i) = \frac{P(\theta_i) + P(\theta_{-i})}{2} \quad (\text{A.1})$$

where

$P_F(\theta_i)$ is the folded power curve;

$P(\theta_{-i})$ is the measured power as a function of the angular position, θ_i (radians), indexed by i .

A.3.2 Compute the top (T) and bottom (B) integrals of Formula (1)

Use an appropriate numerical integration technique to compute the integrals of Formula (1). The following is an example using the rectangular method. Any other integration method shall be at least as accurate as this one.

$$T = \sum_0^n P_F(\theta_i) \sin(\theta_i) \cos(\theta_i) d\theta \quad (\text{A.2})$$

$$B = \sum_0^n P_F(\theta_i) \sin^3(\theta_i) \cos(\theta_i) d\theta \quad (\text{A.3})$$

where

P_F is the folded power curve;

θ_i is the angular position, indexed by i (radians);

$d\theta = \theta_1 - \theta_0$.

A.3.3 Complete the calculation

$$\text{MFD} = 2W_0 = \left(\frac{\lambda\sqrt{2}}{\pi} \right) \sqrt{\frac{T}{B}} \quad (\text{A.4})$$

where

$2W_0$ is the mode field diameter, in μm ;

T is from Formula (A.2);

B is from Formula (A.3).

A.4 Sample data

See Table E.1 for a sample data set as calculated in Clause A.3.

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Annex B (normative)

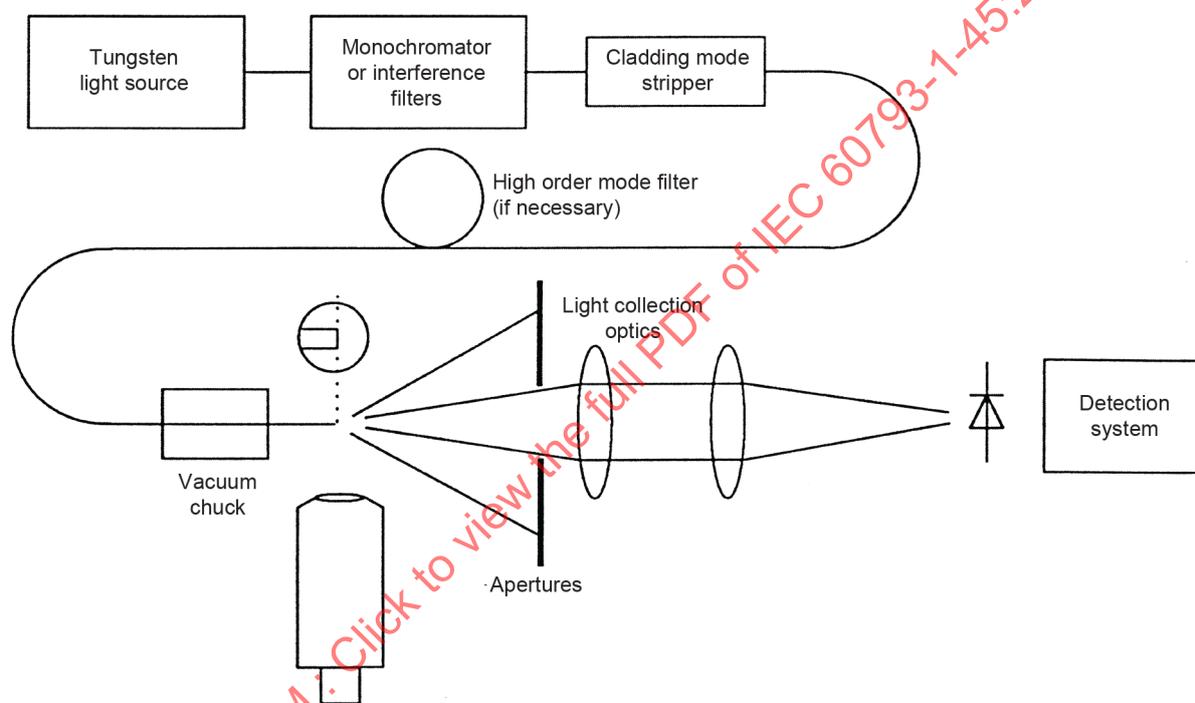
Requirements specific to method B – Mode field diameter by variable aperture in the far field

B.1 Apparatus

B.1.1 General

Annex B describes apparatus in addition to the requirements in Clause 6.

Figure B.1 illustrates a typical set-up for the measurement by variable aperture in the far field.



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Figure B.1 – Variable aperture by far-field measurement set

B.1.2 Output variable aperture assembly

B.1.2.1 Principle

Place a device consisting of round, transmitting apertures of various sizes (such as an aperture wheel) at a distance of at least $100 W_0^2/\lambda$ from the ~~specimen~~ sample, and use it to vary the power detected from the fibre output far field pattern. Typically, the apertures are located 20 mm to 50 mm away from the fibre end.

Use a means of centring the apertures with respect to the pattern to decrease the sensitivity to fibre end angle. Use a sufficient number and size of apertures such that the measurement results are not unduly affected by the inclusion of any additional aperture. In addition, take care to ensure that the largest apertures are of sufficient size to avoid truncation of the collected pattern.

NOTE 1 Optical alignment is critical.

NOTE 2 The number and size of the apertures are critical to the accuracy of this method. The optimum can vary depending on the design of the fibres being tested. Verification of a particular selection can be completed by comparison with method A, direct far-field.

B.1.2.2 Equipment requirements for category ~~B1 and B6~~ B-652, B-654 and B-657 fibre

The accuracy of the mode field diameter measurement given by this procedure depends on the maximum numerical aperture of the measurement set. For category ~~B1 and B6~~ B-652, B-654, and B-657 fibre, the error is typically 1 % or less for a measurement set with a maximum numerical aperture of 0,25. If less error is desired, or if the ~~specimen~~ sample has a mode field diameter less than 8,2 µm, use either of two approaches:

- a) use a measurement system with a maximum numerical aperture of 0,35 or greater; or
- b) determine a mapping function that relates the measurement of category ~~B1 and B6~~ B-652, B-654, and B-657 fibre on limited aperture measurement set to that of a set with 0,35 or greater numerical aperture.

B.1.2.3 Equipment requirements for category ~~B2, B4, and B5~~ B-653, B-655, and B-656 fibres

The maximum numerical aperture of the measurement set shall be ≥0,40 for fibres with mode field diameters ≥6 µm.

B.1.3 Output optics system

Use an optical system, such as a pair of lenses, mirrors, or other suitable arrangement, to collect all the light transmitted through the aperture, and to couple it to the detector.

B.1.4 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 can include a germanium or InGaAs photodiode, operating in the photovoltaic mode, and a current-sensitive preamplifier, with synchronous detection by a lock-in amplifier. Generally, a computer is required to analyze the data.

B.2 Procedure

- a) Place the ~~specimen~~ sample, prepared as described in Clause 6, in the input and output alignment devices, and adjust it for the correct distance to the aperture assembly.
- a) Set the aperture assembly to a small aperture and adjust the far field to an aperture lateral alignment for maximum detected power.
- b) Measure the detected power for each of the apertures.
- c) Calculate the mode field diameter per Formula (2) and Clause B.3.
- d) Repeat steps b), c) and d) for each specified measurement wavelength.

B.3 Calculations

B.3.1 Determine complementary aperture function

Determine the complementary aperture function for each aperture, from 1 to *n*:

$$a(\theta_i) = 1 - \frac{P(\theta_i)}{P(\theta_n)} \tag{B.1}$$

where

a(*θ*_{*i*}) is the complementary function for each aperture, indexed with *i* , from 1 to *n*;

$P(\theta_i)$ is the measured power as a function of the angular position, θ_i , indexed by i .

B.3.2 Complete the integration

Use an appropriate numerical integration technique to compute the integrals of Formula (5). The following is an example. Any other integration method shall be at least as accurate as this example.

$$T = \sum_1^n a(\theta_i) \sin(2\theta_i)(\theta_i - \theta_{i-1}) \quad (\text{B.2})$$

where

T is the top integral of Formula (1);

$a(\theta_i)$ is the complementary aperture function from Formula (B.1).

NOTE $\theta_0 = 0$

B.3.3 Complete the calculation

$$\text{MFD} = 2W_0 = \left(\frac{\lambda}{\pi}\right) \sqrt{\frac{2}{T}} \quad (\text{B.3})$$

where

$2W_0$ is the mode field diameter in micrometres (μm);

T is from Formula (B.2).

B.4 Sample data

See Table E.2 for a sample data set as calculated in Clause B.3.

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Annex C
(normative)

**Requirements specific to method C –
Mode field diameter by near-field scan**

C.1 Apparatus

C.1.1 General

Annex C describes apparatus in addition to the requirements in Clause 6.

Figure C.1 illustrates a typical set-up for the measurement by near-field scan.

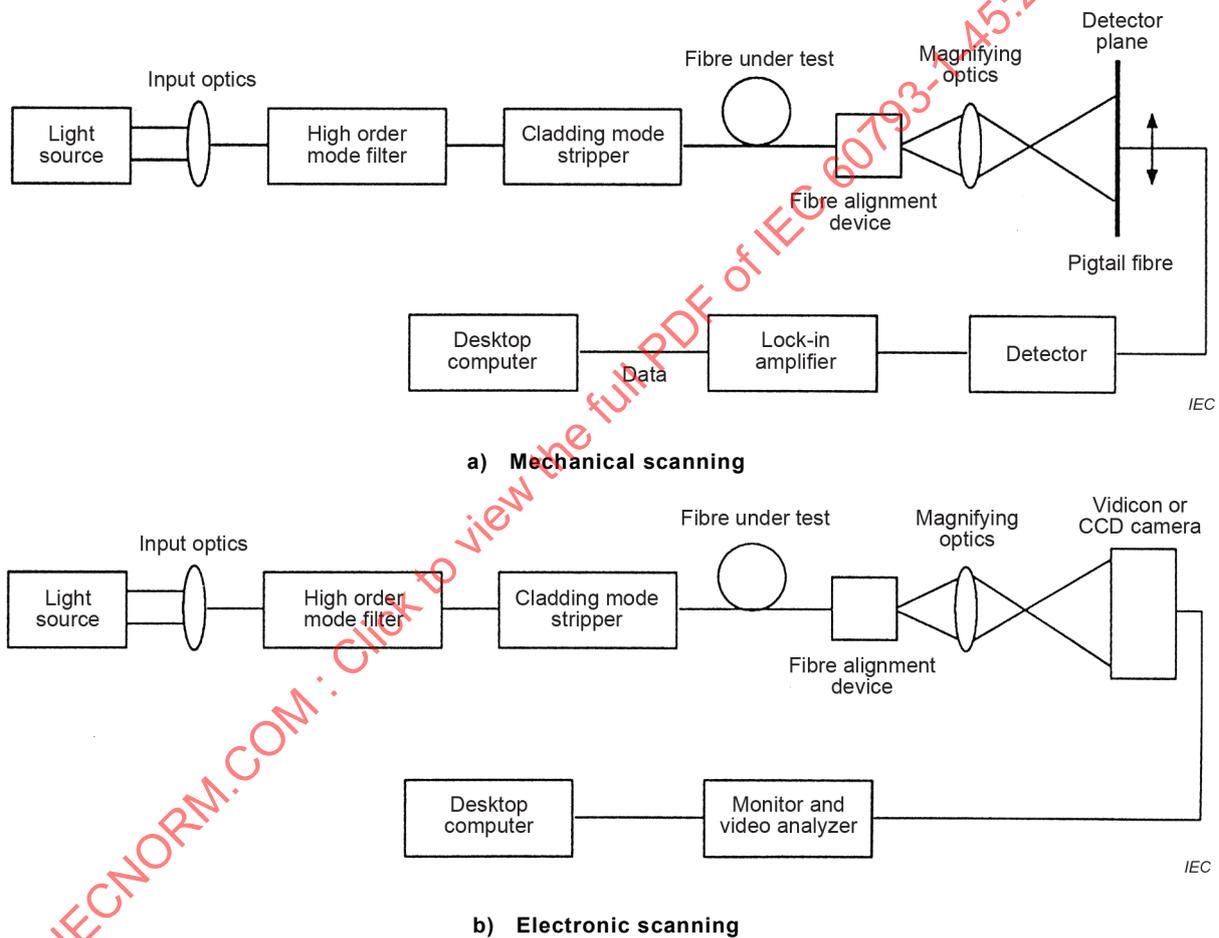


Figure C.1 – Near-field measurement set-ups

C.1.2 Magnifying output optics

Use a suitable optical system (for example a microscopic objective) to magnify the output end of the ~~specimen~~ sample, focusing it onto the plane of the scanning detector. These optics shall not restrict the numerical aperture of the formed image and shall have a numerical aperture greater than the maximum NA of the fibre output radiation and larger than 0,45 for ~~B2 and B3~~ B-653, B-655, and B-656 fibres, and larger than 0,35 for ~~B1~~ B-652, B-654, and B-657 fibres.

C.1.3 Scanning detector

Use a suitable scanning detector to measure the point-to-point intensity of the transmitted near field pattern. The detector shall be linear over the range of intensities encountered.

Use a scanning system (mechanical or electronic) that permits a suitable resolution of the near-field image (typically 100 points or more along a range of the near-field pattern, which is about three times the nominal mode field diameter reported to the fibre surface).

For example, any of the following techniques can be used:

- a) a fixed photo detector in which the field is scanned by a scanning pigtail fibre;
- b) a scanning vidicon, charge-coupled devices (CCD) or other pattern/intensity recognition devices.

Accurately calibrate such devices in position.

C.1.4 Detection electronics

To increase the signal level, use a suitable electronic system. Choose the bandwidth of such an electronic system according to type of technique used.

When scanning the output end of the fibre with a mechanical or optical system, it is customary to modulate the optical source. If adopting such a procedure, link the amplifier (for example lock-in amplifier) to the source modulation frequency. When performing the scanning electronically, use a suitable video analyzing system and a system for automatic scanning of the near-field image, data acquisition, and processing.

C.2 Procedure

- a) Place the ~~specimen~~ sample, prepared as described in Clause 6, in the input and output alignment devices, and adjust it for correct distance to the magnifying optics in such a way as to be focused onto the plane of the scanning detector. The criterion of maximizing the contrast of the image can be used for a proper focus.
- b) Either scan the magnified near-field pattern by moving the scanning fibre and recording the detected intensity as a function of position or process the near-field pattern by means of a video analyzer, according to whether the scanning is mechanical or electronic, respectively.
- c) Calculate the value of the mode field diameter from the near-field intensity pattern, $f^2(r)$, expressed on the fibre output face, considering the magnification and the actual radial coordinate, r , according to Clause C.3.
- d) Periodically measure the magnification of the magnifying optics in conjunction with the scanning system. Perform the initial calibration using a suitable calibrated grating, and then periodically check it by scanning the image of a fibre end face whose dimensions are known with suitable accuracy.

C.3 Calculations

C.3.1 Calculate the centroid

For a given cross section of the near-field test pattern that is of maximum extent, calculate the centroid position as follows:

$$r_c = \frac{\sum r_i f^2(r_i)}{\sum f^2(r_i)} \quad (\text{C.1})$$

where

r_c is the centroid position;

r_i are the position values;

$f^2(r_i)$ are the intensity values.

C.3.2 Fold the intensity profile

Re-index the position and intensity data around the position centroid from Formula (C.1) so that positions above have index values greater than zero, and positions below have index values less than zero. The maximum index is given as n . The folded index profile is

$$f_f^2(r_i) = \left[\frac{f^2(r_i) + f^2(r_{-i})}{2} \right] \tag{C.2}$$

$f_f^2(r_i)$ is the folded intensity value;

$f^2(r_i)$ are the intensity values.

C.3.3 Compute the integrals

Use an appropriate numerical integration technique to compute the integrals of Formula (6). The following is an example. Any other integration method shall be at least as accurate.

Compute the top and bottom integrals of Formula (6) as follows:

$$T = \sum_0^n r_i f_f^2(r_i) dr \tag{C.3}$$

where

T is the top integral of Formula (6);

r_i are the position values;

$f_f^2(r_i)$ are the folded intensity profiles.

$$B = \sum_0^n r_i \left[\frac{df_f(r_i)}{dr} \right]^2 dr \tag{C.4}$$

where

B is the bottom integral of Formula (6);

$df_f(r_i) = f_f(r_i) - f_f(r_{i-1})$ for $i > 0$, or 0 for $i = 0$;

$dr = (r_1 - r_0)$.

The data may be fitted to a curve for the computation of the derivative.

C.3.4 Complete the calculation

$$\text{MFD} = 2W_0 = 2\sqrt{\frac{2T}{B}} \quad (\text{C.5})$$

where

$2W_0$ is the mode field diameter in μm ;

T is from Formula (C.3);

B is from Formula (C.4).

C.4 Sample data

See Table E.1 for a sample data set as calculated in Clause C.3.

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Annex D (normative)

Requirements specific to method D – Mode field diameter by optical time domain reflectometer (OTDR)

D.1 General

This method describes the calculation of mode field diameter at the fibre ends using the results of bi-directional backscatter measurements from an optical time domain reflectometer (OTDR).

The measurement is made by comparison to a reference pigtail fibre with a known value of mode field diameter at the pigtail fibre ends. This reference fibre should be of a similar single-mode design as the fibre that is being characterized, for example, matched cladding ~~B4~~ B-652 type fibre. An empirical mapping can sometimes be used for characterization of a fibre of one design with a reference fibre of another design. This mapping is specific to the design pair.

The measurement is limited to mode field diameter at the reference-sample joint because OTDRs are non-linear. This attribute is often specified by instrument manufacturers. Although typical specification values are sufficient for attenuation coefficient measurements, they are not sufficiently stringent to allow accurate characterization of mode field diameter over the entire fibre length. Bi-directional backscatter traces are required to characterize mode field diameter.

This method is most often used in manufacturing, where the fibre design is well known. The latter methods shall be used to resolve disputes in value. Periodic validation of the results of this method is recommended.

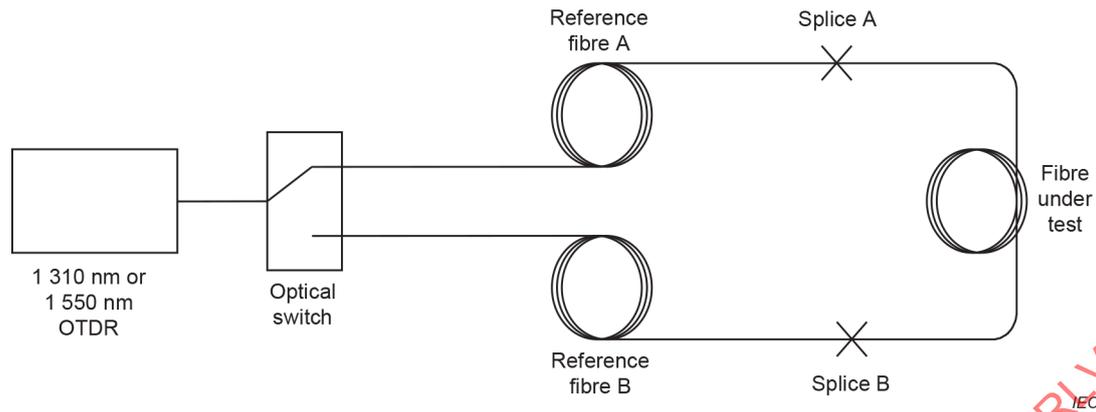
D.2 Apparatus

D.2.1 OTDR

The equipment is described in method C – Backscattering of IEC 60793-1-40. The actual centre wavelengths of the OTDR should be known to within 2 nm for best results. An error of 2,5 nm will cause about a 0,025 μm error in the mode field diameter when wavelengths in the 1 310 nm and 1 550 nm region are used.

D.2.2 Optional auxiliary switches

Various optical switching schemes can be used to make this method more efficient. Figure D.1 illustrates an example in which an OTDR with lasers at two wavelengths is employed to carry out bi-directional backscattering measurements. The two reference fibres allow characterization of both ends of the fibre under test.



The splices can be butt joints and shall be stable for the duration of the measurement.

Figure D.1 – Optical switch arrangement

D.2.3 Optional computer

A computer, used for evaluating the loss across the splices, is recommended.

D.2.4 Test sample

The sample is a type B single-mode fibre, wound on a reel or in a cable, long enough to exceed (or positioned beyond) the dead zone of the OTDR, with both ends accessible, as described in the backscatter test of IEC 60793-1-40.

D.2.5 Reference sample

Use a single-mode fibre which has been measured for mode field diameter at one or more wavelengths. Two reference fibres, one for each end of the ~~specimen~~ sample, may be used.

The reference fibre is typically of the same design as the fibre under test and is of a length sufficient to avoid the OTDR dead-zone. If the reference fibre is not of the same design as the fibre under test, a mapping of the values generated by this method and the values generated by a primary method shall be completed.

D.3 Procedure – Orientation and notation

This method describes the characterization of position A of Figure D.1. The notation of Clause D.3 can be inverted for characterization of position B. The backscatter loss across position A is measured by launching light from one or more wavelengths into both reference fibre A and reference fibre B.

For this procedure, the following symbols are used:

λ_j is a particular wavelength;

RFA is reference fibre A;

RFB is reference fibre B;

$L_A(\lambda_j)$ is the loss across splice A when launching λ_j through RFA;

$L_B(\lambda_j)$ is the loss across splice A when launching λ_j through RFB;

$W_A(\lambda_j)$ is the measured mode field diameter at λ_j at the end of RFA;

$W_S(\lambda_j)$ is the mode field diameter at λ_j derived from this method for the ~~specimen~~ sample.

Figure D.2 and Figure D.3 show these loss values on two backscatter traces.

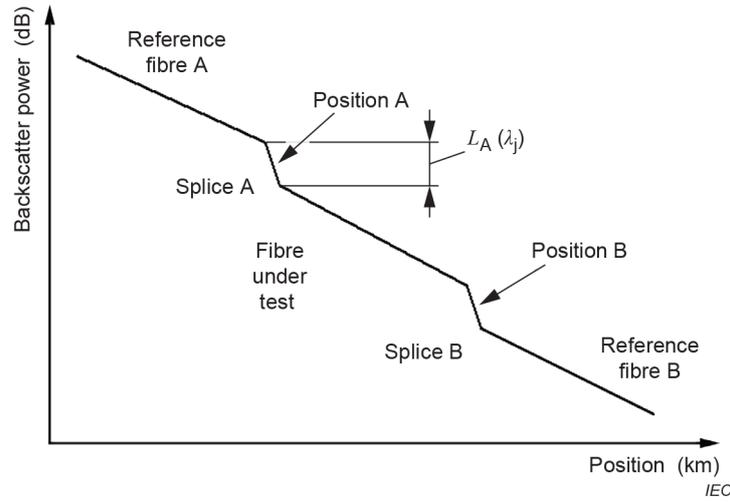


Figure D.2 – View from reference fibre A

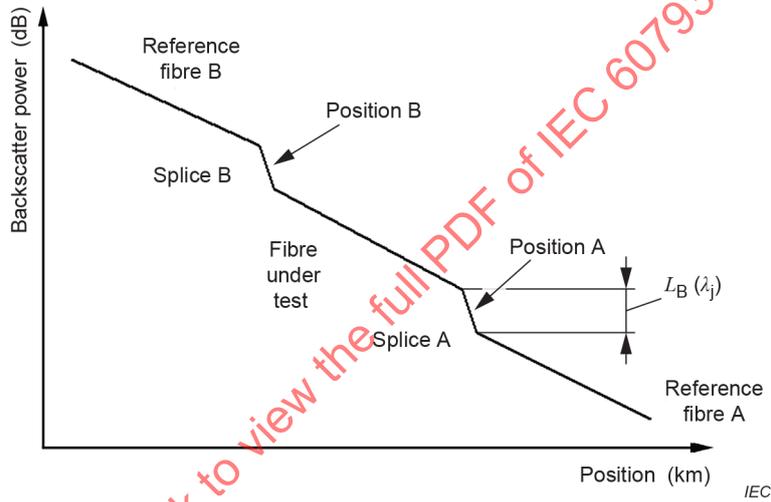


Figure D.3 – View from reference fibre B

The loss across splice A is measured using ~~C.3.6~~ Method C (Backscattering) of IEC 60793-1-40:2004 when launching light at λ_j from RFA. The result is recorded as $L_A(\lambda_j)$. The loss across the same splice A is measured using ~~C.3.6~~ Method C (Backscattering) of IEC 60793-1-40:2004 when launching light at λ_j from RFB. The result is recorded as $L_B(\lambda_j)$.

D.4 Calculations

D.4.1 Reference fibre mode field diameter

The mode field diameter of reference fibre A should be measured at each desired wavelength.

D.4.2 Computation of the ~~specimen~~ sample mode field diameter

For each desired wavelength, λ_j , the difference in loss between RFA and RFB views is computed as follows:

$$\Delta L(\lambda_j) = L_A(\lambda_j) - L_B(\lambda_j) \tag{D.1}$$

The mode field diameter of the specimen sample at λ_j is computed as follows:

$$W_S(\lambda_j) = W_A(\lambda_j) 10^{\left[\frac{g_j \Delta L(\lambda_j) + f_j}{20} \right]} \quad (\text{D.2})$$

The parameters g_j and f_j allow improvements in the result. For a given product design, g_j and f_j values that optimize accuracy may be determined experimentally by validation, see details in D.4.3. Alternatively, g_j and f_j may be set to values of 1 and 0, respectively.

D.4.3 Validation

Figure D.4 illustrates a validation plot.

A sample of the population of the fibre design is measured with both a primary method and this method. The sample should cover a broad range of mode field diameter and cut-off values.

The values of this method are plotted against the values from the primary method to verify that an essentially linear relationship is present. The slope of the line should be close to unity and the intercept should be close to zero. The best test for non-unit slopes is to correlate the paired differences with the paired totals. If the correlation is not significant, the slope is not significantly different than 1. Bias, or non-zero intercept, is addressed in the numerical case illustrated by Figure D.4.

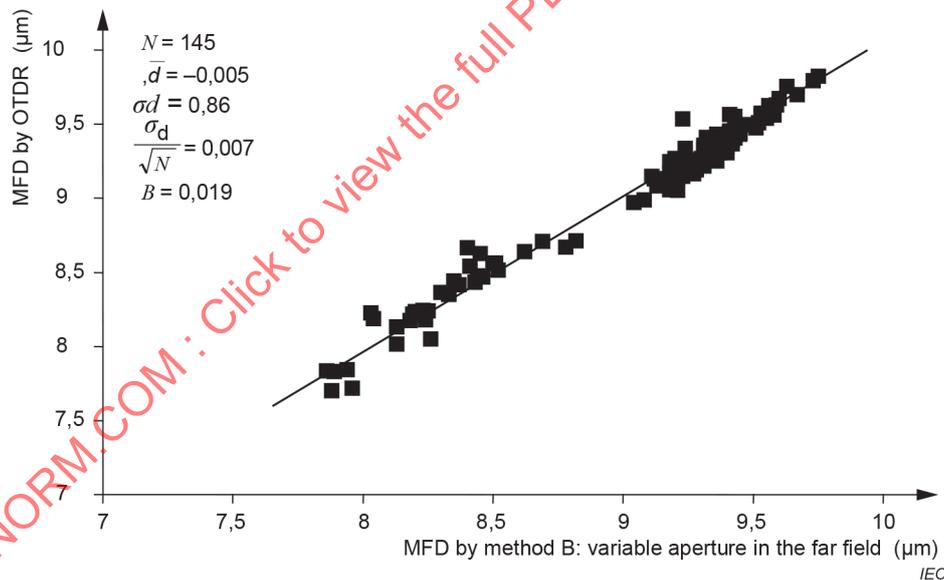


Figure D.4 – Validation example – Comparison of methods

The paired difference, d_i , between the values of this method and the primary methods is computed for each specimen sample, indexed with i , from 1 to N . A histogram is formed of these paired differences and the average, \bar{d} , and standard deviation, σ_d , of these differences are computed. The empirical accuracy is represented as follows:

$$B = \left| \bar{d} \right| + 2 \frac{\sigma_d}{\sqrt{N}} \quad (\text{D.3})$$

If B is too large, i.e. larger than expected between two instruments using other methods from this document, refinement of the formulae or of the procedure is recommended. A typical maximum value of B is 0,1 μm .

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Annex E (informative)

Sample data sets and calculated values

E.1 General

Table E.1, Table E.2, and Table E.3 represent sample data and calculated values obtained from Annex A, Annex B and Annex C, respectively.

E.2 Method A – Mode field diameter by direct far-field scan

Table E.1 – Sample data, method A – Mode field diameter by direct far-field scan

| Angle ° | Folded power | Angle ° | Folded power |
|------------|--------------|------------|--------------|
| 0,000 | 1,000 00 | 9,405 | 0,048 47 |
| 0,495 | 0,986 26 | 9,900 | 0,039 11 |
| 0,990 | 0,944 69 | 10,395 | 0,031 55 |
| 1,485 | 0,881 28 | 10,890 | 0,025 58 |
| 1,980 | 0,802 91 | 11,385 | 0,020 59 |
| 2,475 | 0,713 44 | 11,880 | 0,016 59 |
| 2,970 | 0,621 16 | 12,375 | 0,013 35 |
| 3,465 | 0,533 03 | 12,870 | 0,010 77 |
| 3,960 | 0,452 02 | 13,365 | 0,008 65 |
| 4,455 | 0,378 06 | 13,860 | 0,006 97 |
| 4,950 | 0,313 73 | 14,355 | 0,005 59 |
| 5,445 | 0,258 48 | 14,850 | 0,004 47 |
| 5,940 | 0,211 16 | 15,345 | 0,003 56 |
| 6,435 | 0,171 70 | 15,840 | 0,002 83 |
| 6,930 | 0,139 50 | 16,335 | 0,002 24 |
| 7,425 | 0,113 30 | 16,830 | 0,001 79 |
| 7,920 | 0,091 99 | 17,325 | 0,001 45 |
| 8,415 | 0,074 47 | 17,820 | 0,001 13 |
| 8,910 | 0,060 09 | 18,315 | 0,000 87 |

Wavelength: 1 550 nm.
Calculated mode field diameter: 6,73 µm.

E.3 Method B – Mode field diameter by variable aperture in the far field

Details of the calculation method ~~may~~ can cause differences in computed value on the order of 0,01 µm.

Table E.2 – Sample data set, method B – Mode field diameter by variable aperture in the far field

| θ_i ° | Power | θ_i ° | Power |
|-----------------|----------|-----------------|----------|
| 1,273 | 0,085 72 | 10,367 | 0,708 23 |
| 2,201 | 0,208 64 | 11,172 | 0,714 50 |
| 2,930 | 0,312 50 | 11,944 | 0,719 71 |
| 3,820 | 0,423 22 | 13,216 | 0,725 10 |
| 4,631 | 0,509 08 | 14,879 | 0,729 71 |
| 5,403 | 0,567 77 | 16,671 | 0,733 06 |
| 6,271 | 0,613 60 | 18,275 | 0,734 74 |
| 7,107 | 0,646 90 | 20,042 | 0,735 82 |
| 7,776 | 0,667 85 | 21,788 | 0,735 84 |
| 8,663 | 0,686 43 | 23,478 | 0,736 16 |
| 9,558 | 0,699 63 | - | - |

Wavelength: 1 550 nm.
Calculated mode field diameter: 8,13 µm.

E.4 Method C – Mode field diameter by near-field scan

A sample data set and the calculation of mode field diameter appears in Table E.3.

Table E.3 – Sample data set, method C – Mode field diameter by near-field scan

| r µm | $f^2(r)/I(0)$ | r µm | $f^2(r)/I(0)$ |
|-----------|---------------|-----------|---------------|
| 0,000 | 1,000 00 | 10,817 | 0,001 97 |
| 1,082 | 0,890 27 | 11,899 | 0,000 88 |
| 2,163 | 0,635 61 | 12,981 | 0,000 36 |
| 3,245 | 0,350 31 | 14,063 | 0,000 15 |
| 4,327 | 0,166 87 | 15,144 | 0,000 06 |
| 5,409 | 0,078 26 | 16,226 | 0,000 02 |
| 6,490 | 0,037 35 | 17,308 | 0,000 00 |
| 7,572 | 0,017 52 | 18,389 | 0,000 00 |
| 8,654 | 0,008 72 | 19,471 | 0,000 00 |
| 9,736 | 0,004 33 | 20,553 | 0,000 00 |

Wavelength: 1 550 nm.
Calculated mode field diameter: 10,48 µm.

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IEC 60793-2, *Optical fibres – Part 2: Product specifications – General*

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Optical fibres –

Part 1-45: Measurement methods and test procedures – Mode field diameter

Fibres optiques –

Partie 1-45 : Méthodes de mesure et procédures d'essai – Diamètre du champ de mode

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CONTENTS

| | |
|--|----|
| FOREWORD..... | 5 |
| 1 Scope..... | 7 |
| 2 Normative references | 7 |
| 3 Terms, definitions and abbreviated terms | 7 |
| 3.1 Terms and definitions..... | 7 |
| 3.2 Abbreviated terms..... | 7 |
| 4 General consideration about mode field diameter | 8 |
| 5 Reference test method | 8 |
| 6 Apparatus..... | 8 |
| 6.1 General..... | 8 |
| 6.2 Light source | 9 |
| 6.3 Input optics | 9 |
| 6.4 Input positioner | 9 |
| 6.5 Cladding mode stripper | 9 |
| 6.6 High-order mode filter | 9 |
| 6.7 Output positioner | 9 |
| 6.8 Output optics | 10 |
| 6.9 Detector..... | 10 |
| 6.10 Computer..... | 10 |
| 7 Sampling and samples..... | 10 |
| 7.1 Sample length..... | 10 |
| 7.2 Sample end face..... | 10 |
| 8 Procedure..... | 10 |
| 9 Calculations..... | 10 |
| 9.1 Basic formulae | 10 |
| 9.2 Method A – Direct far-field scan..... | 10 |
| 9.3 Method B – Variable aperture in the far field | 11 |
| 9.4 Method C – Near-field scan..... | 12 |
| 10 Results | 13 |
| 10.1 Information available with each measurement..... | 13 |
| 10.2 Information available upon request | 13 |
| 11 Specification information | 13 |
| Annex A (normative) Requirements specific to method A – Mode field diameter by direct far-field scan | 14 |
| A.1 Apparatus | 14 |
| A.1.1 General | 14 |
| A.1.2 Scanning detector assembly – Signal detection electronics | 14 |
| A.1.3 Computer..... | 15 |
| A.2 Procedure | 15 |
| A.3 Calculations | 15 |
| A.3.1 Determine folded power curve | 15 |
| A.3.2 Compute the top (T) and bottom (B) integrals of Formula (1) | 15 |
| A.3.3 Complete the calculation | 16 |
| A.4 Sample data | 16 |
| Annex B (normative) Requirements specific to method B – Mode field diameter by variable aperture in the far field | 17 |

| | | |
|---|--|----|
| B.1 | Apparatus | 17 |
| B.1.1 | General | 17 |
| B.1.2 | Output variable aperture assembly | 17 |
| B.1.3 | Output optics system | 18 |
| B.1.4 | Detector assembly and signal detection electronics | 18 |
| B.2 | Procedure | 18 |
| B.3 | Calculations | 18 |
| B.3.1 | Determine complementary aperture function | 18 |
| B.3.2 | Complete the integration | 19 |
| B.3.3 | Complete the calculation | 19 |
| B.4 | Sample data | 19 |
| Annex C (normative) Requirements specific to method C – Mode field diameter by near-field scan | | 20 |
| C.1 | Apparatus | 20 |
| C.1.1 | General | 20 |
| C.1.2 | Magnifying output optics | 20 |
| C.1.3 | Scanning detector | 21 |
| C.1.4 | Detection electronics | 21 |
| C.2 | Procedure | 21 |
| C.3 | Calculations | 21 |
| C.3.1 | Calculate the centroid | 21 |
| C.3.2 | Fold the intensity profile | 22 |
| C.3.3 | Compute the integrals | 22 |
| C.3.4 | Complete the calculation | 23 |
| C.4 | Sample data | 23 |
| Annex D (normative) Requirements specific to method D – Mode field diameter by optical time domain reflectometer (OTDR) | | 24 |
| D.1 | General | 24 |
| D.2 | Apparatus | 24 |
| D.2.1 | OTDR | 24 |
| D.2.2 | Optional auxiliary switches | 24 |
| D.2.3 | Optional computer | 25 |
| D.2.4 | Test sample | 25 |
| D.2.5 | Reference sample | 25 |
| D.3 | Procedure – Orientation and notation | 25 |
| D.4 | Calculations | 26 |
| D.4.1 | Reference fibre mode field diameter | 26 |
| D.4.2 | Computation of the sample mode field diameter | 27 |
| D.4.3 | Validation | 27 |
| Annex E (informative) Sample data sets and calculated values | | 29 |
| E.1 | General | 29 |
| E.2 | Method A – Mode field diameter by direct far-field scan | 29 |
| E.3 | Method B – Mode field diameter by variable aperture in the far field | 30 |
| E.4 | Method C – Mode field diameter by near-field scan | 30 |
| Bibliography | | 31 |
| Figure 1 – Transform relationships between measurement results | | 8 |
| Figure A.1 – Far-field measurement set | | 14 |

Figure B.1 – Variable aperture by far-field measurement set..... 17

Figure C.1 – Near-field measurement set-ups 20

Figure D.1 – Optical switch arrangement 25

Figure D.2 – View from reference fibre A 26

Figure D.3 – View from reference fibre B 26

Figure D.4 – Validation example – Comparison of methods..... 27

Table 1 – Abbreviated terms 7

Table E.1 – Sample data, method A – Mode field diameter by direct far-field scan 29

Table E.2 – Sample data set, method B – Mode field diameter by variable aperture in the far field 30

Table E.3 – Sample data set, method C – Mode field diameter by near-field scan 30

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

OPTICAL FIBRES –

**Part 1-45: Measurement methods and test procedures –
Mode field diameter**

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IEC 60793-1-45 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 2017. This edition constitutes a technical revision.

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

- a) Modification of the minimum distance between the fibre end and the detector for the direct far field scan (Annex A).
- b) Generalization of the requirement for the minimum dynamic range for all fibre types (Annex A).

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

| Draft | Report on voting |
|--------------|------------------|
| 86A/2300/CDV | 86A/2366/RVC |

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.

A list of all parts in the IEC 60793 series, published under the general title *Optical fibres*, 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,
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OPTICAL FIBRES –

Part 1-45: Measurement methods and test procedures – Mode field diameter

1 Scope

This part of IEC 60793 establishes uniform requirements for measuring the mode field diameter (MFD) of single-mode optical fibre, thereby assisting in the inspection of fibres and cables for commercial purposes.

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 60793-1-40, *Optical fibres – Part 1-40: Attenuation measurement methods*

3 Terms, definitions and abbreviated terms

3.1 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>

3.2 Abbreviated terms

The abbreviated terms are given in Table 1.

Table 1 – Abbreviated terms

| Abbreviated term | Full term |
|------------------|-----------------------------------|
| CCD | charge-coupled devices |
| FWHM | full width half maximum |
| MFD | mode field diameter |
| OTDR | optical time domain reflectometer |
| RTM | reference test method |

4 General consideration about mode field diameter

The mode field diameter measurement represents a measure of the transverse extent of the electromagnetic field intensity of the guided mode in a fibre cross section, and it is defined from the far-field intensity distribution as a ratio of integrals known as the Petermann II definition. See Formula (1).

The definitions of mode field diameter are strictly related to the measurement configurations. The mathematical equivalence of these definitions results from transform relationships between measurement results obtained by different implementations summarized in Figure 1.

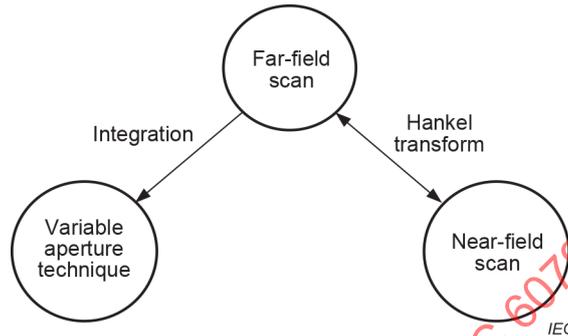


Figure 1 – Transform relationships between measurement results

Four methods are described for measuring mode field diameter:

- method A: direct far-field scan;
- method B: variable aperture in the far field;
- method C: near-field scan;
- method D: bi-directional backscatter using an optical time domain reflectometer (OTDR).

All four methods apply to all categories of type B single-mode fibre shown in IEC 60793-2 and operating near 1 310 nm or 1 550 nm. Method D is not recommended for the measurement of fibres of unknown type or design.

Information common to all four methods is contained in Clause 1 to Clause 11, and information pertaining to each individual method appears in Annex A, Annex B, Annex C, and Annex D respectively.

5 Reference test method

Method A, direct far-field scan, is the reference test method (RTM), which shall be the one used to settle disputes.

6 Apparatus

6.1 General

The following apparatus is common to all measurement methods. Annex A, Annex B, Annex C, and Annex D include layout drawings and other equipment requirements for each of the four methods, respectively.

6.2 Light source

For method A, method B and method C, use a suitable coherent or non-coherent light source, such as a semiconductor laser or a powerful filtered white light source.

A monochromator or interference filter(s) may be used, if required, for wavelength selection. The detail specification shall indicate the wavelength of the source. The full width half maximum (FWHM) spectral line width of the source shall ≤ 10 nm, unless otherwise specified.

The source power level shall be chosen so it is not impacting the repeatability of the mode diameter measurement.

The source power shall be stable for the complete duration of the measurement.

See Annex D for method D.

6.3 Input optics

For method A, method B, and method C, an optical lens system or fibre pigtail may be employed to excite the sample. It is recommended that the power coupled into the sample be relatively insensitive to the position of its input end face. This can be accomplished by using a launch beam that spatially and angularly overfills the input end face.

If using a butt splice, employ index-matching material between the fibre pigtail and the sample to avoid interference effects. The coupling shall be stable for the duration of the measurement.

See Annex D for method D.

6.4 Input positioner

Provide means of positioning the input end of the sample to the light source. Examples include the use of x-y-z micropositioner stages, or mechanical coupling devices such as connectors, vacuum splices, or three-rod splices. The position of the fibre shall remain stable over the duration of the measurement.

6.5 Cladding mode stripper

Use a device that extracts cladding modes. Under some circumstances, the fibre coating will perform this function.

6.6 High-order mode filter

Use a means to remove high-order propagating modes in the wavelength range that is greater than or equal to the cut-off wavelength of the sample. For example, a one-turn bend with a radius of 30 mm on the fibre is generally sufficient for most B-652, B-653, B-654, B-655, B-656 and B-657 fibres. For some B-657 fibres, smaller radius, multiple bends, or longer sample length can be applied to remove high-order propagating modes.

6.7 Output positioner

Provide a suitable means for aligning the fibre output end face to allow an accurate axial adjustment of the output end, such that, at the measurement wavelength, the scan pattern is suitably focused on the plane of the scanning detector. Such coupling may include the use of lenses or a mechanical connector to a detector pigtail.

Provide means such as a side-viewing microscope or camera with a crosshair to locate the fibre at a fixed distance from the apertures or detectors. It can be sufficient to provide only longitudinal adjustment if the fibre is constrained in the lateral plane by a device such as a vacuum chuck (this depends mainly upon the size of the light detector).

6.8 Output optics

See the appropriate annex: Annex A, Annex B, Annex C or Annex D.

6.9 Detector

See the appropriate annex: Annex A, Annex B, Annex C or Annex D.

6.10 Computer

Use a computer to perform operations such as controlling the apparatus, taking intensity measurements, and processing the data to obtain the final results. For individual details, see the appropriate annex: Annex A, Annex B, Annex C or Annex D.

7 Sampling and samples

7.1 Sample length

For method A, method B and method C, the sample shall be a known length, typically $2\text{ m} \pm 0,2\text{ m}$ for most B-652, B-653, B-654, B-655, B-656 and B-657 fibres. For some B-657 fibres, longer sample length can be used to avoid high-order propagating modes, 22 m for example.

For method D, OTDR, the sample shall be long enough to exceed (or be positioned beyond) the dead zone of the OTDR, with both ends accessible, as described in the backscatter test method in IEC 60793-1-40.

7.2 Sample end face

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

8 Procedure

See Annex A, Annex B, Annex C and Annex D for method A, method B, method C, and method D, respectively.

9 Calculations

9.1 Basic formulae

The basic formulae for calculating mode field diameter are Formula (1) for method A, Formula (2) for method B and Formula (6) for method C. For additional calculations, see the appropriate annex: Annex A, Annex B, Annex C or Annex D. Sample data sets for method A, method B and method C are included in Annex E.

9.2 Method A – Direct far-field scan

The following formula defines the mode field diameter for method A in terms of the electromagnetic field emitted from the end of the sample.

Calculate the mode field diameter by scanning the far-field data and evaluating the Petermann II integral, which is defined from the far-field intensity distribution:

$$2W_0 = \frac{\lambda\sqrt{2}}{\pi} \left[\frac{\int_0^{\pi/2} P_F(\theta) \sin(\theta) \cos(\theta) d\theta}{\int_0^{\pi/2} P_F(\theta) \sin^3(\theta) \cos(\theta) d\theta} \right]^{1/2} \quad (1)$$

where

$2W_0$ is the mode field diameter in μm ;

$P_F(\theta)$ is the far-field intensity distribution;

λ is the wavelength of measurement in μm ;

θ is the angle in the far-field measurement from the axis of the fibre.

NOTE 1 The integration limits are shown to be from zero to $\pi/2$, but it is understood that the integrands approach zero with increasing argument so that, in practice, the integrals can be truncated.

NOTE 2 P_F is $F^2(\theta)$ in ITU-T documents.

The far-field method for obtaining the mode field diameter of a single-mode fibre is a two-step procedure. First, measure the far-field radiation pattern of the fibre. Second, use a mathematical procedure based on the Petermann II far-field definition to calculate the mode field from far-field data, as described in Formula (1).

Annex E provides sample data and calculated $2W_0$ values for verifying the numerical evaluation of the Petermann II Integral. The sample data are in the form of the folded power, $P_F(\theta)$, as a function of the angle, θ .

9.3 Method B – Variable aperture in the far field

Formula (2) defines the mode field diameter for method B in terms of the electromagnetic field emitted from the end of the sample.

Calculate the mode field diameter, $2W_0$, as follows:

$$2W_0 = \left(\frac{\lambda}{\pi D} \right) \left[\int_0^{\infty} a(x) \frac{x}{(x^2 + D^2)^2} dx \right]^{-1/2} \quad (2)$$

where

$2W_0$ is the mode field diameter, in μm ;

λ is the wavelength of measurement, in μm ;

D is the distance between the aperture and the fibre, in mm;

$a(x)$ is the complementary aperture transmission function, calculated as

$$a(x) = 1 - \frac{P(x)}{P(\max)} \quad (3)$$

where

$P_{(x)}$ is the power measured through an aperture of radius, x , or half angle, θ ;

$P_{(max)}$ is the maximum power, assuming an infinite aperture;

x is the aperture radius, calculated as

$$x = D \tan(\theta) \tag{4}$$

Another equivalent expression of Formula (2) is

$$2W_0 = \frac{\lambda\sqrt{2}}{\pi} \left[\int_0^\infty a(\theta) \sin 2\theta d\theta \right]^{-1/2} \tag{5}$$

The variable aperture far-field method for obtaining the mode field diameter of a single-mode fibre is a two-step procedure. First, measure the two-dimensional far-field pattern as the power passing through a series of transmitting apertures of various size. Second, use a mathematical procedure to calculate the mode field diameter from the far-field data.

The mathematical basis for the calculation of mode field diameter is based on the Petermann II far-field definition from Formula (1). Formula (2) and Formula (5) can be derived from Formula (1) by integration.

9.4 Method C – Near-field scan

The following formula defines the mode field diameter for method C in terms of the electromagnetic field emitted from the end of the sample.

Calculate the mode field diameter from the measured near-field intensity distribution, using the following integral:

$$2W_0 = 2 \left(\frac{\int_0^\infty r f^2(r) dr}{\int_0^\infty r \left(\frac{df(r)}{dr} \right)^2 dr} \right)^{1/2} \tag{6}$$

where

$2W_0$ is the mode field diameter, in μm ;

r is the radial coordinate, in μm ;

$f^2(r)$ is the near-field intensity distribution.

NOTE The upper integration limits are shown to infinity, but it is understood that since the integrands approach zero with increasing argument, in practice the integrals can be truncated. A smoothing algorithm can be used for the calculation of the derivative.

The near-field scan method for obtaining the mode field diameter of a single-mode fibre is a two-step procedure. First, measure the radial near-field pattern. Second, use a mathematical procedure to calculate the mode field diameter from the near-field data.

The mathematical basis for the calculation of the mode field diameter is based on the Petermann II definition from Formula (1). The near field, $f(r)$, and the far field, $F(\theta)$, form a Hankel transform pair. By Hankel transforming and using $P_F = F^2(\theta)$, it is possible to derive Formula (6) from Formula (1), and vice versa.

10 Results

10.1 Information available with each measurement

Report the following information with each measurement:

- date and title of measurement;
- identification of sample;
- optical source wavelength;
- mode field diameter(s), in micrometres.

10.2 Information available upon request

The following information shall be available upon request:

- measurement method used: method A, method B, method C or method D;
- type of optical source used and its spectral width (FWHM);
- description of equipment;
- description of high-order modes filter;
- details of computation technique;
- date of latest calibration of measurement equipment.

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 –
Mode field diameter by direct far-field scan**

A.1 Apparatus

A.1.1 General

Annex A describes apparatus in addition to the requirements set down in Clause 6.

Figure A.1 illustrates a typical set-up for measurement by direct far-field scan.

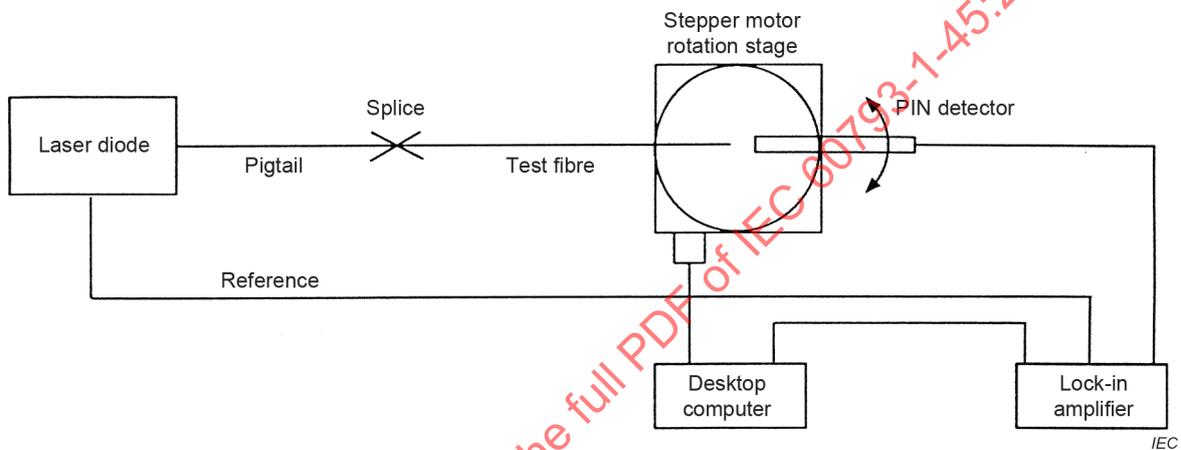


Figure A.1 – Far-field measurement set

A.1.2 Scanning detector assembly – Signal detection electronics

Use a mechanism to scan the far-field intensity distribution. Use a scanning device capable of 0,5° steps or finer to scan the detector. Use a means of aligning the fibre axis with respect to the rotation plane of the detector, and of aligning the fibre end-face with the centre of rotation of the scan. A typical system might include a PIN photodiode, operating in a photovoltaic mode, amplified by a current-input preamplifier, with synchronous detection by a lock-in amplifier. The detector should be at least 10 mm from the fibre end (to ensure the detector to scan the far field), and the detector's active area should not subtend an angle too large in the far field.

To ensure this, place the detector at a distance d from the fibre end with $d = K \times \frac{2w.b}{\lambda}$

where

$2w$ is the expected mode field diameter of the sample,

b is the diameter of the active area of the detector,

λ is the wavelength,

K is the resolution factor which value is big enough to prevent the degradation of the far field scan and its impact on the calculation of the mode field diameter.

A value of K , greater than 20, is suitable for most fibre types and guarantees less than 0,1 % of error in the mode field diameter calculation.

For accurate measurements, the dynamic range of the measurement should be greater than 50 dB. The maximum scan half-angle depends on the fibre type and should be chosen so that the far field scan is characterized down to 50 dB of the maximum signal.

Reducing the dynamic range (or maximum scan half-angle) requirements can introduce errors.

A.1.3 Computer

A typical system should also include a computer to process the far-field data.

A.2 Procedure

Align the fibre in the system, prepared as described in Clause 6, with its output end aligned on the detector assembly for maximum power.

Scan the detector in $0,5^\circ$ steps, equally spaced, and record the detector power.

Calculate a value of the Petermann II integral from the recorded data and use it to compute the fibre mode field diameter as described in Formula (1), and in Clause A.3.

A.3 Calculations

A.3.1 Determine folded power curve

The folded power curve for $0 \leq \theta_i = \theta_{\max}$ is

$$P_F(\theta_i) = \frac{P(\theta_i) + P(\theta_{-i})}{2} \quad (\text{A.1})$$

where

$P_F(\theta_i)$ is the folded power curve;

$P(\theta_{-i})$ is the measured power as a function of the angular position, θ_i (radians), indexed by i .

A.3.2 Compute the top (T) and bottom (B) integrals of Formula (1)

Use an appropriate numerical integration technique to compute the integrals of Formula (1). The following is an example using the rectangular method. Any other integration method shall be at least as accurate as this one.

$$T = \sum_0^n P_F(\theta_i) \sin(\theta_i) \cos(\theta_i) d\theta \quad (\text{A.2})$$

$$B = \sum_0^n P_F(\theta_i) \sin^3(\theta_i) \cos(\theta_i) d\theta \quad (\text{A.3})$$

where

P_F is the folded power curve;

θ_i is the angular position, indexed by i (radians);

$d\theta = \theta_1 - \theta_0$.

A.3.3 Complete the calculation

$$\text{MFD} = 2W_0 = \left(\frac{\lambda\sqrt{2}}{\pi} \right) \sqrt{\frac{T}{B}} \quad (\text{A.4})$$

where

$2W_0$ is the mode field diameter, in μm ;

T is from Formula (A.2);

B is from Formula (A.3).

A.4 Sample data

See Table E.1 for a sample data set as calculated in Clause A.3.

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Annex B (normative)

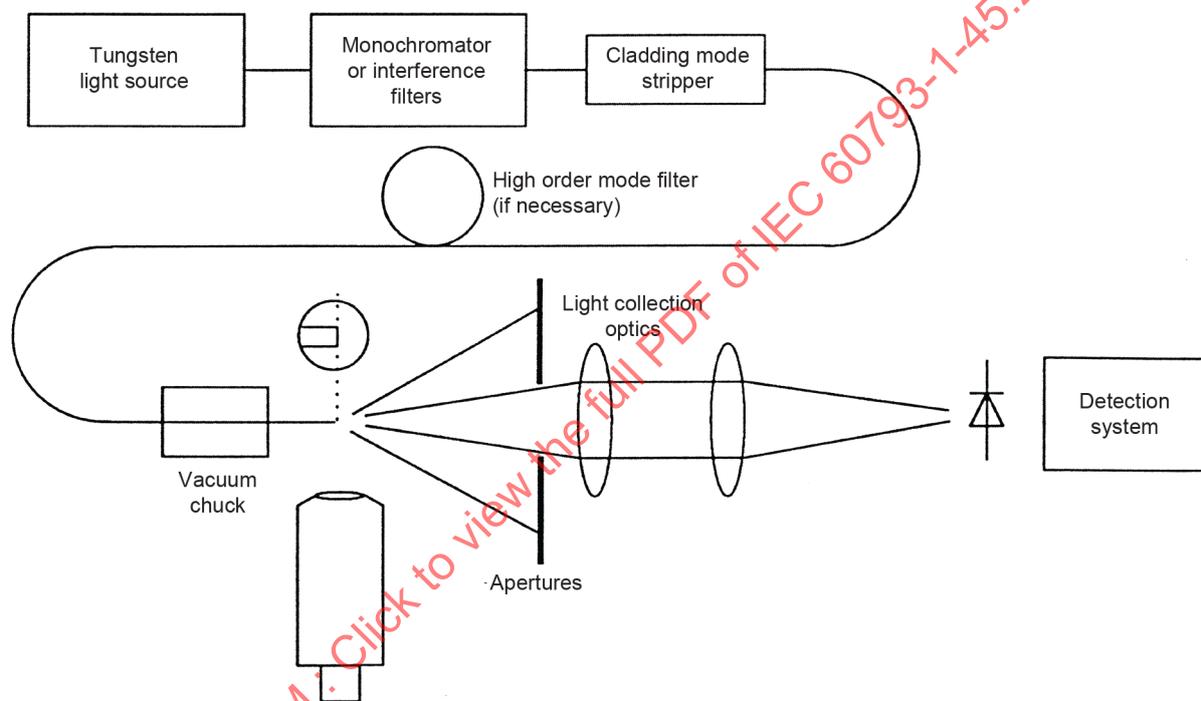
Requirements specific to method B – Mode field diameter by variable aperture in the far field

B.1 Apparatus

B.1.1 General

Annex B describes apparatus in addition to the requirements in Clause 6.

Figure B.1 illustrates a typical set-up for the measurement by variable aperture in the far field.



IEC

Figure B.1 – Variable aperture by far-field measurement set

B.1.2 Output variable aperture assembly

B.1.2.1 Principle

Place a device consisting of round, transmitting apertures of various sizes (such as an aperture wheel) at a distance of at least $100 W_0^2/\lambda$ from the sample, and use it to vary the power detached from the fibre output far field pattern. Typically, the apertures are located 20 mm to 50 mm away from the fibre end.

Use a means of centring the apertures with respect to the pattern to decrease the sensitivity to fibre end angle. Use a sufficient number and size of apertures such that the measurement results are not unduly affected by the inclusion of any additional aperture. In addition, take care to ensure that the largest apertures are of sufficient size to avoid truncation of the collected pattern.

NOTE 1 Optical alignment is critical.

NOTE 2 The number and size of the apertures are critical to the accuracy of this method. The optimum can vary depending on the design of the fibres being tested. Verification of a particular selection can be completed by comparison with method A, direct far-field.

B.1.2.2 Equipment requirements for category B-652, B-654 and B-657 fibre

The accuracy of the mode field diameter measurement given by this procedure depends on the maximum numerical aperture of the measurement set. For category B-652, B-654, and B-657 fibre, the error is typically 1 % or less for a measurement set with a maximum numerical aperture of 0,25. If less error is desired, or if the sample has a mode field diameter less than 8,2 μm , use either of two approaches:

- a) use a measurement system with a maximum numerical aperture of 0,35 or greater; or
- b) determine a mapping function that relates the measurement of category B-652, B-654, and B-657 fibre on limited aperture measurement set to that of a set with 0,35 or greater numerical aperture.

B.1.2.3 Equipment requirements for category B-653, B-655, and B-656 fibres

The maximum numerical aperture of the measurement set shall be $\geq 0,40$ for fibres with mode field diameters $\geq 6 \mu\text{m}$.

B.1.3 Output optics system

Use an optical system, such as a pair of lenses, mirrors, or other suitable arrangement, to collect all the light transmitted through the aperture, and to couple it to the detector.

B.1.4 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 can include a germanium or InGaAs photodiode, operating in the photovoltaic mode, and a current-sensitive preamplifier, with synchronous detection by a lock-in amplifier. Generally, a computer is required to analyze the data.

B.2 Procedure

- a) Place the sample, prepared as described in Clause 6, in the input and output alignment devices, and adjust it for the correct distance to the aperture assembly.
- b) Set the aperture assembly to a small aperture and adjust the far field to an aperture lateral alignment for maximum detected power.
- c) Measure the detected power for each of the apertures.
- d) Calculate the mode field diameter per Formula (2) and Clause B.3.
- e) Repeat steps b), c) and d) for each specified measurement wavelength.

B.3 Calculations

B.3.1 Determine complementary aperture function

Determine the complementary aperture function for each aperture, from 1 to n :

$$a(\theta_i) = 1 - \frac{P(\theta_i)}{P(\theta_n)} \quad (\text{B.1})$$

where

$a(\theta_i)$ is the complementary function for each aperture, indexed with i , from 1 to n ;

$P(\theta_i)$ is the measured power as a function of the angular position, θ_i , indexed by i .

B.3.2 Complete the integration

Use an appropriate numerical integration technique to compute the integrals of Formula (5). The following is an example. Any other integration method shall be at least as accurate as this example.

$$T = \sum_1^n a(\theta_i) \sin(2\theta_i) (\theta_i - \theta_{i-1}) \quad (\text{B.2})$$

where

T is the top integral of Formula (1);

$a(\theta_i)$ is the complementary aperture function from Formula (B.1).

NOTE $\theta_0 = 0$

B.3.3 Complete the calculation

$$\text{MFD} = 2W_0 = \left(\frac{\lambda}{\pi}\right) \sqrt{\frac{2}{T}} \quad (\text{B.3})$$

where

$2W_0$ is the mode field diameter in micrometres (μm);

T is from Formula (B.2).

B.4 Sample data

See Table E.2 for a sample data set as calculated in Clause B.3.

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Annex C
(normative)

**Requirements specific to method C –
Mode field diameter by near-field scan**

C.1 Apparatus

C.1.1 General

Annex C describes apparatus in addition to the requirements in Clause 6.

Figure C.1 illustrates a typical set-up for the measurement by near-field scan.

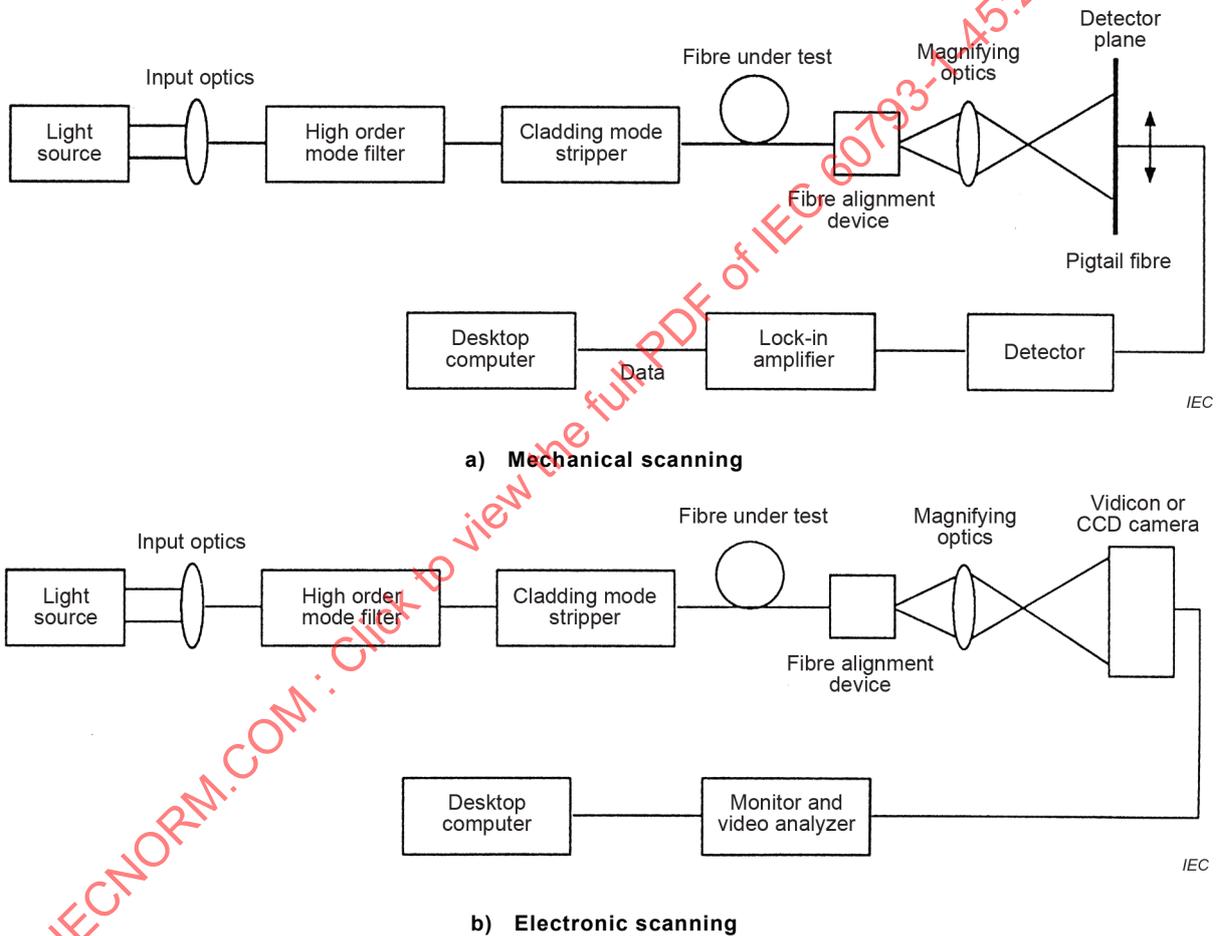


Figure C.1 – Near-field measurement set-ups

C.1.2 Magnifying output optics

Use a suitable optical system (for example a microscopic objective) to magnify the output end of the sample, focusing it onto the plane of the scanning detector. These optics shall not restrict the numerical aperture of the formed image and shall have a numerical aperture greater than the maximum NA of the fibre output radiation and larger than 0,45 for B-653, B-655, and B-656 fibres, and larger than 0,35 for B-652, B-654, and B-657 fibres.

C.1.3 Scanning detector

Use a suitable scanning detector to measure the point-to-point intensity of the transmitted near field pattern. The detector shall be linear over the range of intensities encountered.

Use a scanning system (mechanical or electronic) that permits a suitable resolution of the near-field image (typically 100 points or more along a range of the near-field pattern, which is about three times the nominal mode field diameter reported to the fibre surface).

For example, any of the following techniques can be used:

- a) a fixed photo detector in which the field is scanned by a scanning pigtail fibre;
- b) a scanning vidicon, charge-coupled devices (CCD) or other pattern/intensity recognition devices.

Accurately calibrate such devices in position.

C.1.4 Detection electronics

To increase the signal level, use a suitable electronic system. Choose the bandwidth of such an electronic system according to type of technique used.

When scanning the output end of the fibre with a mechanical or optical system, it is customary to modulate the optical source. If adopting such a procedure, link the amplifier (for example lock-in amplifier) to the source modulation frequency. When performing the scanning electronically, use a suitable video analyzing system and a system for automatic scanning of the near-field image, data acquisition, and processing.

C.2 Procedure

- a) Place the sample, prepared as described in Clause 6, in the input and output alignment devices, and adjust it for correct distance to the magnifying optics in such a way as to be focused onto the plane of the scanning detector. The criterion of maximizing the contrast of the image can be used for a proper focus.
- b) Either scan the magnified near-field pattern by moving the scanning fibre and recording the detected intensity as a function of position or process the near-field pattern by means of a video analyzer, according to whether the scanning is mechanical or electronic, respectively.
- c) Calculate the value of the mode field diameter from the near-field intensity pattern, $f^2(r)$, expressed on the fibre output face, considering the magnification and the actual radial coordinate, r , according to Clause C.3.
- d) Periodically measure the magnification of the magnifying optics in conjunction with the scanning system. Perform the initial calibration using a suitable calibrated grating, and then periodically check it by scanning the image of a fibre end face whose dimensions are known with suitable accuracy.

C.3 Calculations

C.3.1 Calculate the centroid

For a given cross section of the near-field test pattern that is of maximum extent, calculate the centroid position as follows:

$$r_c = \frac{\sum r_i f^2(r_i)}{\sum f^2(r_i)} \quad (\text{C.1})$$

where

r_c is the centroid position;

r_i are the position values;

$f^2(r_i)$ are the intensity values.

C.3.2 Fold the intensity profile

Re-index the position and intensity data around the position centroid from Formula (C.1) so that positions above have index values greater than zero, and positions below have index values less than zero. The maximum index is given as n . The folded index profile is

$$f_f^2(r_i) = \left[\frac{f^2(r_i) + f^2(r_{-i})}{2} \right] \quad (C.2)$$

$f_f^2(r_i)$ is the folded intensity value;

$f^2(r_i)$ are the intensity values.

C.3.3 Compute the integrals

Use an appropriate numerical integration technique to compute the integrals of Formula (6). The following is an example. Any other integration method shall be at least as accurate.

Compute the top and bottom integrals of Formula (6) as follows:

$$T = \sum_0^n r_i f_f^2(r_i) dr \quad (C.3)$$

where

T is the top integral of Formula (6);

r_i are the position values;

$f_f^2(r_i)$ are the folded intensity profiles.

$$B = \sum_0^n r_i \left[\frac{df_f(r_i)}{dr} \right]^2 dr \quad (C.4)$$

where

B is the bottom integral of Formula (6);

$df_f(r_i) = f_f(r_i) - f_f(r_{i-1})$ for $i > 0$, or 0 for $i = 0$;

$dr = (r_1 - r_0)$.

The data may be fitted to a curve for the computation of the derivative.

C.3.4 Complete the calculation

$$\text{MFD} = 2W_0 = 2\sqrt{\frac{2T}{B}} \quad (\text{C.5})$$

where

$2W_0$ is the mode field diameter in μm ;

T is from Formula (C.3);

B is from Formula (C.4).

C.4 Sample data

See Table E.1 for a sample data set as calculated in Clause C.3.

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Annex D (normative)

Requirements specific to method D – Mode field diameter by optical time domain reflectometer (OTDR)

D.1 General

This method describes the calculation of mode field diameter at the fibre ends using the results of bi-directional backscatter measurements from an optical time domain reflectometer (OTDR).

The measurement is made by comparison to a reference pigtail fibre with a known value of mode field diameter at the pigtail fibre ends. This reference fibre should be of a similar single-mode design as the fibre that is being characterized, for example, matched cladding B-652 type fibre. An empirical mapping can sometimes be used for characterization of a fibre of one design with a reference fibre of another design. This mapping is specific to the design pair.

The measurement is limited to mode field diameter at the reference-sample joint because OTDRs are non-linear. This attribute is often specified by instrument manufacturers. Although typical specification values are sufficient for attenuation coefficient measurements, they are not sufficiently stringent to allow accurate characterization of mode field diameter over the entire fibre length. Bi-directional backscatter traces are required to characterize mode field diameter.

This method is most often used in manufacturing, where the fibre design is well known. The latter methods shall be used to resolve disputes in value. Periodic validation of the results of this method is recommended.

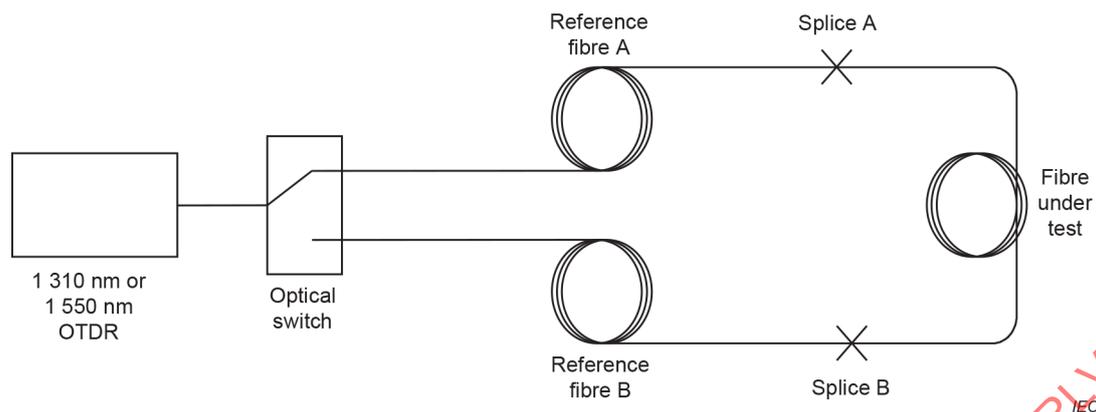
D.2 Apparatus

D.2.1 OTDR

The equipment is described in method C – Backscattering of IEC 60793-1-40. The actual centre wavelengths of the OTDR should be known to within 2 nm for best results. An error of 2,5 nm will cause about a 0,025 μm error in the mode field diameter when wavelengths in the 1 310 nm and 1 550 nm region are used.

D.2.2 Optional auxiliary switches

Various optical switching schemes can be used to make this method more efficient. Figure D.1 illustrates an example in which an OTDR with lasers at two wavelengths is employed to carry out bi-directional backscattering measurements. The two reference fibres allow characterization of both ends of the fibre under test.



The splices can be butt joints and shall be stable for the duration of the measurement.

Figure D.1 – Optical switch arrangement

D.2.3 Optional computer

A computer, used for evaluating the loss across the splices, is recommended.

D.2.4 Test sample

The sample is a type B single-mode fibre, wound on a reel or in a cable, long enough to exceed (or positioned beyond) the dead zone of the OTDR, with both ends accessible, as described in the backscatter test of IEC 60793-1-40.

D.2.5 Reference sample

Use a single-mode fibre which has been measured for mode field diameter at one or more wavelengths. Two reference fibres, one for each end of the sample, may be used.

The reference fibre is typically of the same design as the fibre under test and is of a length sufficient to avoid the OTDR dead-zone. If the reference fibre is not of the same design as the fibre under test, a mapping of the values generated by this method and the values generated by a primary method shall be completed.

D.3 Procedure – Orientation and notation

This method describes the characterization of position A of Figure D.1. The notation of Clause D.3 can be inverted for characterization of position B. The backscatter loss across position A is measured by launching light from one or more wavelengths into both reference fibre A and reference fibre B.

For this procedure, the following symbols are used:

λ_j is a particular wavelength;

RFA is reference fibre A;

RFB is reference fibre B;

$L_A(\lambda_j)$ is the loss across splice A when launching λ_j through RFA;

$L_B(\lambda_j)$ is the loss across splice A when launching λ_j through RFB;

$W_A(\lambda_j)$ is the measured mode field diameter at λ_j at the end of RFA;

$W_S(\lambda_j)$ is the mode field diameter at λ_j derived from this method for the sample.

Figure D.2 and Figure D.3 show these loss values on two backscatter traces.

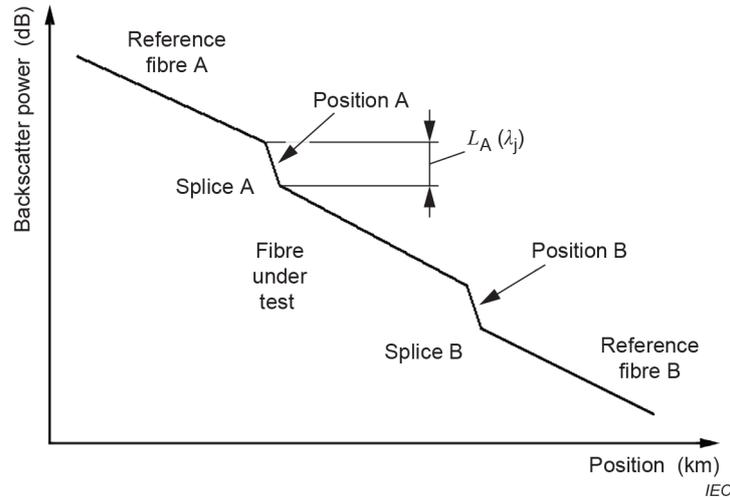


Figure D.2 – View from reference fibre A

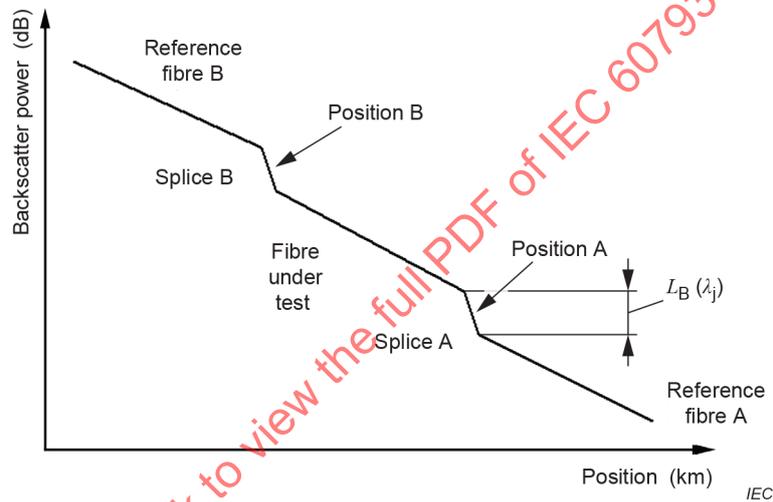


Figure D.3 – View from reference fibre B

The loss across splice A is measured using Method C (Backscattering) of IEC 60793-1-40 when launching light at λ_j from RFA. The result is recorded as $L_A(\lambda_j)$. The loss across the same splice A is measured using Method C (Backscattering) of IEC 60793-1-40 when launching light at λ_j from RFB. The result is recorded as $L_B(\lambda_j)$.

D.4 Calculations

D.4.1 Reference fibre mode field diameter

The mode field diameter of reference fibre A should be measured at each desired wavelength.

D.4.2 Computation of the sample mode field diameter

For each desired wavelength, λ_j , the difference in loss between RFA and RFB views is computed as follows:

$$\Delta L(\lambda_j) = L_A(\lambda_j) - L_B(\lambda_j) \quad (\text{D.1})$$

The mode field diameter of the sample at λ_j is computed as follows:

$$W_S(\lambda_j) = W_A(\lambda_j) 10^{\left[g_j \Delta L(\lambda_j) + f_j \right] / 20} \quad (\text{D.2})$$

The parameters g_j and f_j allow improvements in the result. For a given product design, g_j and f_j values that optimize accuracy may be determined experimentally by validation, see details in D.4.3. Alternatively, g_j and f_j may be set to values of 1 and 0, respectively.

D.4.3 Validation

Figure D.4 illustrates a validation plot.

A sample of the population of the fibre design is measured with both a primary method and this method. The sample should cover a broad range of mode field diameter and cut-off values.

The values of this method are plotted against the values from the primary method to verify that an essentially linear relationship is present. The slope of the line should be close to unity and the intercept should be close to zero. The best test for non-unit slopes is to correlate the paired differences with the paired totals. If the correlation is not significant, the slope is not significantly different than 1. Bias, or non-zero intercept, is addressed in the numerical case illustrated by Figure D.4.

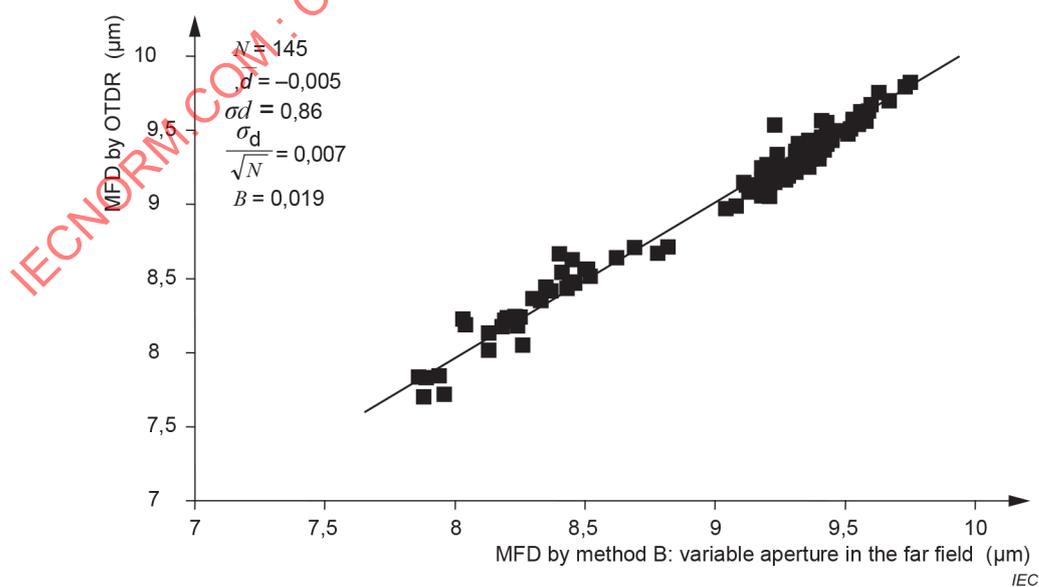


Figure D.4 – Validation example – Comparison of methods

The paired difference, d_i , between the values of this method and the primary methods is computed for each sample, indexed with i , from 1 to N . A histogram is formed of these paired differences and the average, \bar{d} , and standard deviation, σd , of these differences are computed. The empirical accuracy is represented as follows:

$$B = \left| \bar{d} \right| + 2 \frac{\sigma d}{\sqrt{N}} \quad (\text{D.3})$$

If B is too large, i.e. larger than expected between two instruments using other methods from this document, refinement of the formulae or of the procedure is recommended. A typical maximum value of B is 0,1 μm .

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Annex E (informative)

Sample data sets and calculated values

E.1 General

Table E.1, Table E.2, and Table E.3 represent sample data and calculated values obtained from Annex A, Annex B and Annex C, respectively.

E.2 Method A – Mode field diameter by direct far-field scan

Table E.1 – Sample data, method A – Mode field diameter by direct far-field scan

| Angle ° | Folded power | Angle ° | Folded power |
|------------|--------------|------------|--------------|
| 0,000 | 1,000 00 | 9,405 | 0,048 47 |
| 0,495 | 0,986 26 | 9,900 | 0,039 11 |
| 0,990 | 0,944 69 | 10,395 | 0,031 55 |
| 1,485 | 0,881 28 | 10,890 | 0,025 58 |
| 1,980 | 0,802 91 | 11,385 | 0,020 59 |
| 2,475 | 0,713 44 | 11,880 | 0,016 59 |
| 2,970 | 0,621 16 | 12,375 | 0,013 35 |
| 3,465 | 0,533 03 | 12,870 | 0,010 77 |
| 3,960 | 0,452 02 | 13,365 | 0,008 65 |
| 4,455 | 0,378 06 | 13,860 | 0,006 97 |
| 4,950 | 0,313 73 | 14,355 | 0,005 59 |
| 5,445 | 0,258 48 | 14,850 | 0,004 47 |
| 5,940 | 0,211 16 | 15,345 | 0,003 56 |
| 6,435 | 0,171 70 | 15,840 | 0,002 83 |
| 6,930 | 0,139 50 | 16,335 | 0,002 24 |
| 7,425 | 0,113 30 | 16,830 | 0,001 79 |
| 7,920 | 0,091 99 | 17,325 | 0,001 45 |
| 8,415 | 0,074 47 | 17,820 | 0,001 13 |
| 8,910 | 0,060 09 | 18,315 | 0,000 87 |

Wavelength: 1 550 nm.
Calculated mode field diameter: 6,73 μm .

E.3 Method B – Mode field diameter by variable aperture in the far field

Details of the calculation method can cause differences in computed value on the order of 0,01 µm.

Table E.2 – Sample data set, method B – Mode field diameter by variable aperture in the far field

| θ_i ° | Power | θ_i ° | Power |
|-----------------|----------|-----------------|----------|
| 1,273 | 0,085 72 | 10,367 | 0,708 23 |
| 2,201 | 0,208 64 | 11,172 | 0,714 50 |
| 2,930 | 0,312 50 | 11,944 | 0,719 71 |
| 3,820 | 0,423 22 | 13,216 | 0,725 10 |
| 4,631 | 0,509 08 | 14,879 | 0,729 71 |
| 5,403 | 0,567 77 | 16,671 | 0,733 06 |
| 6,271 | 0,613 60 | 18,275 | 0,734 74 |
| 7,107 | 0,646 90 | 20,042 | 0,735 82 |
| 7,776 | 0,667 85 | 21,788 | 0,735 84 |
| 8,663 | 0,686 43 | 23,478 | 0,736 16 |
| 9,558 | 0,699 63 | - | - |

Wavelength: 1 550 nm.
Calculated mode field diameter: 8,13 µm.

E.4 Method C – Mode field diameter by near-field scan

A sample data set and the calculation of mode field diameter appears in Table E.3.

Table E.3 – Sample data set, method C – Mode field diameter by near-field scan

| r µm | $f^2(r)/I(0)$ | r µm | $f^2(r)/I(0)$ |
|-----------|---------------|-----------|---------------|
| 0,000 | 1,000 00 | 10,817 | 0,001 97 |
| 1,082 | 0,890 27 | 11,899 | 0,000 88 |
| 2,163 | 0,635 61 | 12,981 | 0,000 36 |
| 3,245 | 0,350 31 | 14,063 | 0,000 15 |
| 4,327 | 0,166 87 | 15,144 | 0,000 06 |
| 5,409 | 0,078 26 | 16,226 | 0,000 02 |
| 6,490 | 0,037 35 | 17,308 | 0,000 00 |
| 7,572 | 0,017 52 | 18,389 | 0,000 00 |
| 8,654 | 0,008 72 | 19,471 | 0,000 00 |
| 9,736 | 0,004 33 | 20,553 | 0,000 00 |

Wavelength: 1 550 nm.
Calculated mode field diameter: 10,48 µm.

Bibliography

IEC 60793-2, *Optical fibres – Part 2: Product specifications – General*

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SOMMAIRE

| | |
|---|----|
| AVANT-PROPOS | 35 |
| 1 Domaine d'application | 37 |
| 2 Références normatives | 37 |
| 3 Termes, définitions et termes abrégés | 37 |
| 3.1 Termes et définitions | 37 |
| 3.2 Termes abrégés | 37 |
| 4 Considérations générales concernant le diamètre du champ de mode | 38 |
| 5 Méthode d'essai de référence | 38 |
| 6 Appareillage | 38 |
| 6.1 Généralités | 38 |
| 6.2 Source de lumière | 39 |
| 6.3 Système optique d'entrée | 39 |
| 6.4 Dispositif de positionnement d'entrée | 39 |
| 6.5 Extracteur de modes de gaine | 39 |
| 6.6 Filtre des modes d'ordre supérieur | 39 |
| 6.7 Dispositif de positionnement de sortie | 39 |
| 6.8 Dispositif optique de sortie | 40 |
| 6.9 Détecteur | 40 |
| 6.10 Calculateur | 40 |
| 7 Échantillonnage et échantillons | 40 |
| 7.1 Longueur d'échantillon | 40 |
| 7.2 Extrémité de l'échantillon | 40 |
| 8 Procédure | 40 |
| 9 Calculs | 40 |
| 9.1 Formules de base | 40 |
| 9.2 Méthode A – Exploration directe en champ lointain | 41 |
| 9.3 Méthode B – Ouverture variable en champ lointain | 41 |
| 9.4 Méthode C – Exploration en champ proche | 42 |
| 10 Résultats | 43 |
| 10.1 Informations disponibles pour chaque mesure | 43 |
| 10.2 Informations disponibles sur demande | 43 |
| 11 Informations à mentionner dans la spécification | 43 |
| Annexe A (normative) Exigences spécifiques à la méthode A – Diamètre du champ de mode par la technique de l'exploration directe en champ lointain | 44 |
| A.1 Appareillage | 44 |
| A.1.1 Généralités | 44 |
| A.1.2 Ensemble détecteur à balayage – Système électronique de détection des signaux | 44 |
| A.1.3 Calculateur | 45 |
| A.2 Procédure | 45 |
| A.3 Calculs | 45 |
| A.3.1 Déterminer la courbe de puissance symétrisée par moyennes des écarts | 45 |
| A.3.2 Calculer l'intégrale du numérateur (T) et l'intégrale du dénominateur (B) de la Formule (1) | 45 |
| A.3.3 Effectuer le calcul | 46 |

| | | |
|---|---|----|
| A.4 | Données sur échantillon..... | 46 |
| Annexe B (normative) Exigences spécifiques à la méthode B – Diamètre du champ de mode par la technique de l'ouverture variable en champ lointain..... | | |
| B.1 | Appareillage..... | 47 |
| B.1.1 | Généralités..... | 47 |
| B.1.2 | Ensemble à ouvertures variables de sortie..... | 47 |
| B.1.3 | Dispositifs optiques de sortie..... | 48 |
| B.1.4 | Ensemble détecteur et dispositif électronique de détection des signaux..... | 48 |
| B.2 | Procédure..... | 48 |
| B.3 | Calculs..... | 49 |
| B.3.1 | Déterminer la fonction complémentaire d'ouverture..... | 49 |
| B.3.2 | Effectuer l'intégration..... | 49 |
| B.3.3 | Effectuer le calcul..... | 49 |
| B.4 | Données sur échantillon..... | 49 |
| Annexe C (normative) Exigences spécifiques à la méthode C – Diamètre du champ de mode par la technique de l'exploration en champ proche..... | | |
| C.1 | Appareillage..... | 50 |
| C.1.1 | Généralités..... | 50 |
| C.1.2 | Ensembles optiques de grossissement..... | 51 |
| C.1.3 | Détecteur à balayage..... | 51 |
| C.1.4 | Systèmes électroniques de détection..... | 51 |
| C.2 | Procédure..... | 51 |
| C.3 | Calculs..... | 52 |
| C.3.1 | Calculer le barycentre..... | 52 |
| C.3.2 | Symétriser le profil d'intensité..... | 52 |
| C.3.3 | Calculer les intégrales..... | 52 |
| C.3.4 | Effectuer le calcul..... | 53 |
| C.4 | Données sur échantillon..... | 53 |
| Annexe D (normative) Exigences spécifiques à la méthode D – Diamètre du champ de mode par réflectomètre optique dans le domaine temporel (OTDR)..... | | |
| D.1 | Généralités..... | 54 |
| D.2 | Appareillage..... | 54 |
| D.2.1 | OTDR..... | 54 |
| D.2.2 | Commutateurs auxiliaires facultatifs..... | 54 |
| D.2.3 | Calculateur facultatif..... | 55 |
| D.2.4 | Échantillon d'essai..... | 55 |
| D.2.5 | Échantillon de référence..... | 55 |
| D.3 | Procédure – Orientation et notation..... | 55 |
| D.4 | Calculs..... | 56 |
| D.4.1 | Diamètre du champ de mode de la fibre de référence..... | 56 |
| D.4.2 | Calcul du diamètre du champ de mode de l'échantillon..... | 57 |
| D.4.3 | Validation..... | 57 |
| Annexe E (informative) Ensemble de données sur échantillon et valeurs calculées..... | | |
| E.1 | Généralités..... | 59 |
| E.2 | Méthode A – Diamètre du champ de mode par exploration directe en champ lointain..... | 59 |
| E.3 | Méthode B – Diamètre du champ de mode par la méthode de l'ouverture variable en champ lointain..... | 60 |
| E.4 | Méthode C – Diamètre du champ de mode par exploration en champ proche..... | 61 |

Bibliographie..... 62

Figure 1 – Relations de transformées entre les résultats de mesure 38

Figure A.1 – Montage de mesure en champ lointain..... 44

Figure B.1 – Montage de mesure par ouverture variable en champ lointain..... 47

Figure C.1 – Montages de mesure en champ proche..... 50

Figure D.1 – Montage de commutation optique 55

Figure D.2 – Vue depuis la fibre de référence A..... 56

Figure D.3 – Vue depuis la fibre de référence B..... 56

Figure D.4 – Exemple de validation: comparaison de méthodes 58

Tableau 1 – Termes abrégés 37

Tableau E.1 – Données sur échantillon, méthode A – Diamètre du champ de mode par exploration directe en champ lointain 59

Tableau E.2 – Données sur échantillon, méthode B – Diamètre du champ de mode par la méthode de l’ouverture variable en champ lointain..... 60

Tableau E.3 – Données sur échantillon, méthode C – Diamètre du champ de mode par exploration en champ proche 61

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FIBRES OPTIQUES –

**Partie 1-45: Méthodes de mesure et procédures d'essai –
Diamètre du champ de mode**

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Cette troisième édition annule et remplace la deuxième édition parue en 2017. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

- a) modification de la distance minimale entre l'extrémité de la fibre et le détecteur pour l'exploration directe en champ lointain (Annexe A),
- b) généralisation de l'exigence de plage dynamique minimale pour tous les types de fibres (Annexe A).

Le texte de cette Norme internationale est issu des documents suivants:

| Projet | Rapport de vote |
|--------------|-----------------|
| 86A/2300/CDV | 86A/2366/RVC |

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à son approbation.

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FIBRES OPTIQUES –

Partie 1-45: Méthodes de mesure et procédures d'essai – Diamètre du champ de mode

1 Domaine d'application

La présente partie de l'IEC 60793 établit des exigences harmonisées pour mesurer le diamètre du champ de mode (MFD, *Mode Field Diameter*) d'une fibre optique unimodale, contribuant ainsi au contrôle des fibres et câbles à des fins commerciales.

2 Références normatives

Les documents suivants sont cités dans le texte de sorte qu'ils constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60793-1-40:2019, *Fibres optiques – Partie 1-40: Méthodes de mesurage de l'affaiblissement*

3 Termes, définitions et termes abrégés

3.1 Termes et définitions

Aucun terme n'est défini dans le présent document.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse <https://www.electropedia.org/>
- ISO Online browsing platform: disponible à l'adresse <https://www.iso.org/obp>

3.2 Termes abrégés

Les termes abrégés sont indiqués dans le Tableau 1.

Tableau 1 – Termes abrégés

| Terme abrégé | Français | Anglais |
|--------------|---|-----------------------------------|
| CCD | dispositif à couplage de charge | charge-coupled devices |
| FWHM | largeur de raie spectrale | full width half maximum |
| MFD | diamètre du champ de mode | mode field diameter |
| OTDR | réflectomètre optique fonctionnant dans le domaine temporel | optical time domain reflectometer |
| RTM | méthode d'essai de référence | reference test method |

4 Considérations générales concernant le diamètre du champ de mode

La mesure du diamètre du champ de mode représente une mesure de l'étendue transversale de l'intensité du champ électromagnétique du mode guidé dans la section droite d'une fibre, et il est défini à partir de la distribution de l'intensité du champ lointain comme un rapport d'intégrales, connu comme étant la définition de Petermann II. Voir l'Équation (1).

Les définitions du diamètre du champ de mode sont strictement liées aux configurations de mesure. L'équivalence mathématique de ces définitions résulte des relations de transformées entre les résultats de mesure obtenus par différents outils résumés à la Figure 1.

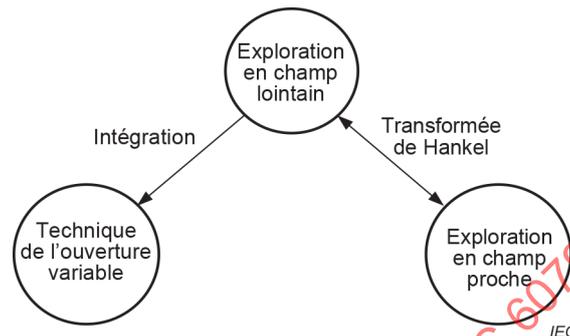


Figure 1 – Relations de transformées entre les résultats de mesure

Quatre méthodes de mesure du diamètre du champ de mode sont décrites:

- méthode A: exploration directe en champ lointain,
- méthode B: ouverture variable en champ lointain,
- méthode C: exploration en champ proche,
- méthode D: rétrodiffusion bidirectionnelle utilisant un réflectomètre optique fonctionnant dans le domaine temporel (OTDR, *Optical Time Domain Reflectometer*).

Ces quatre méthodes s'appliquent à toutes les catégories de fibres unimodales de type B de l'IEC 60793-2 opérant au voisinage de 1 310 nm ou de 1 550 nm. La méthode D n'est pas recommandée pour la mesure des fibres de type ou de modèle inconnus.

Les informations communes aux quatre méthodes sont contenues dans les Articles 1 à 11, et les informations concernant individuellement chaque méthode se trouvent respectivement à l'Annexe A, à l'Annexe B, à l'Annexe C et à l'Annexe D.

5 Méthode d'essai de référence

La méthode A, exploration directe en champ lointain, est la méthode d'essai de référence, qui doit être utilisée pour résoudre les contestations.

6 Appareillage

6.1 Généralités

L'appareillage suivant est commun à toutes les méthodes de mesure. L'Annexe A, l'Annexe B, l'Annexe C et l'Annexe D contiennent respectivement les dessins et les exigences relatives aux autres équipements, pour chacune des quatre méthodes.

6.2 Source de lumière

Pour les méthodes A, B et C, utiliser une source de lumière appropriée, cohérente ou incohérente, telle qu'un laser à semiconducteur ou une source de lumière blanche filtrée suffisamment puissante. La source doit produire un rayonnement suffisant à la ou aux longueurs d'onde voulues et doit être stable en intensité pendant une durée suffisante pour permettre d'effectuer la mesure.

Si cela est exigé, un monochromateur ou un ou des filtres interférentiels peuvent être utilisés pour la sélection des longueurs d'onde. La longueur d'onde de la source doit être indiquée dans la spécification particulière. La largeur de raie spectrale à mi-hauteur (FWHM, *Full Width Half Maximum*) de la source doit être inférieure ou égale à 10 nm, sauf spécification contraire.

Voir l'Annexe D pour la méthode D.

6.3 Système optique d'entrée

Pour les méthodes A, B et C, l'utilisation d'un système de lentilles optiques ou d'une fibre amorce pour exciter l'échantillon est admise. Il est recommandé que la puissance couplée dans l'échantillon soit relativement insensible à la position de l'extrémité d'entrée de l'échantillon. Cela peut être réalisé en utilisant un faisceau d'injection permettant une saturation à la fois spatiale et angulaire de l'extrémité d'entrée.

Si une épissure en bout est utilisée, employer un matériau d'adaptation d'indice entre la fibre amorce et l'échantillon pour éviter les phénomènes d'interférence. Le couplage doit rester stable pendant toute la durée de la mesure.

Voir l'Annexe D pour la méthode D.

6.4 Dispositif de positionnement d'entrée

Prévoir un dispositif pour le positionnement de l'extrémité d'entrée de l'échantillon par rapport à la source de lumière. Des exemples comprennent l'utilisation d'étages de réglage micrométrique en x-y-z ou des dispositifs de couplage mécanique tels que des connecteurs, des épissures sous vide ou des épissures à trois piges. La position de la fibre doit rester stable pendant toute la durée de la mesure.

6.5 Extracteur de modes de gaine

Utiliser un dispositif d'extraction de modes de gaine. Dans certains cas, c'est le revêtement de la fibre qui assure cette fonction.

6.6 Filtre des modes d'ordre supérieur

Utiliser un moyen pour éliminer la propagation des modes d'ordre supérieur dans la plage des longueurs d'onde supérieures ou égales à la longueur d'onde de coupure de l'échantillon. Par exemple, une boucle d'un seul tour d'un rayon de 30 mm sur la fibre d'essai suffit généralement pour la plupart des fibres de type B-652, B-653, B-654, B-655, B-656 et B-657. Pour certaines fibres de type B-657, un rayon plus petit, des boucles plus nombreuses ou une longueur d'échantillon plus importante peuvent être appliqués afin d'éviter la propagation des modes d'ordre supérieur.

6.7 Dispositif de positionnement de sortie

Prévoir un dispositif approprié pour l'alignement de l'extrémité de sortie de la fibre pour permettre un réglage axial précis de l'extrémité de sortie, tel que, à la longueur d'onde de mesure, le balayage soit focalisé convenablement sur le plan du détecteur de balayage. Un tel couplage peut comprendre l'utilisation de lentilles ou peut être un connecteur mécanique à une fibre amorce du détecteur.

Prévoir un moyen tel qu'un microscope à vision latérale ou un appareil photographique équipé d'un réticule pour localiser la fibre à une distance fixe par rapport aux ouvertures ou au détecteur. Un réglage longitudinal seul peut s'avérer suffisant si la fibre est maintenue dans le plan latéral par un dispositif tel qu'un mandrin à succion (cela dépend essentiellement de la taille du détecteur de lumière).

6.8 Dispositif optique de sortie

Voir l'annexe appropriée: Annexe A, Annexe B, Annexe C ou Annexe D.

6.9 Détecteur

Voir l'annexe appropriée: Annexe A, Annexe B, Annexe C ou Annexe D.

6.10 Calculateur

Utiliser un calculateur pour effectuer les opérations telles que la commande de l'appareillage, l'exécution des mesures d'intensité et le traitement des données pour obtenir les résultats finaux. Pour les détails des opérations, voir l'annexe appropriée: Annexe A, Annexe B, Annexe C ou Annexe D.

7 Échantillonnage et échantillons

7.1 Longueur d'échantillon

Pour les méthodes A, B et C, l'échantillon doit être d'une longueur connue, généralement de $2 \text{ m} \pm 0,2 \text{ m}$, pour la plupart des fibres de type B-652, B-653, B-654, B-655, B-656 et B-657. Pour certaines fibres de type B-657, une longueur d'échantillon plus importante peut être appliquée, par exemple de 22 m, afin d'éviter la propagation des modes d'ordre supérieur.

Pour la méthode D à l'OTDR, l'échantillon doit être suffisamment long pour dépasser (ou être placé au-delà de) la zone morte de l'OTDR, avec les deux extrémités accessibles, comme décrit dans la méthode d'essai de rétrodiffusion de l'IEC 60793-1-40.

7.2 Extrémité de l'échantillon

Préparer une surface plane, perpendiculaire à l'axe de la fibre, à l'extrémité d'entrée et à l'extrémité de sortie de chaque échantillon.

8 Procédure

Voir respectivement l'Annexe A, l'Annexe B, l'Annexe C et l'Annexe D pour les méthodes A, B, C et D.

9 Calculs

9.1 Formules de base

Les formules de base pour le calcul du diamètre du champ de mode pour chacune des méthodes A, B, et C sont indiquées ci-après. Pour des calculs supplémentaires, voir l'annexe appropriée: Annexe A, Annexe B, Annexe C ou Annexe D.. Des ensembles de données sur échantillons pour les méthodes A, B et C figurent à l'Annexe E.

9.2 Méthode A – Exploration directe en champ lointain

La formule suivante définit le diamètre du champ de mode pour la méthode A concernant le champ électromagnétique émis à partir de l'extrémité de l'échantillon.

Calculer le diamètre du champ de mode à partir des données de l'exploration en champ lointain et de l'évaluation de l'intégrale de Petermann II, qui est définie à partir de la distribution de l'intensité en champ lointain:

$$2W_0 = \frac{\lambda\sqrt{2}}{\pi} \left[\frac{\int_0^{\pi/2} P_F(\theta) \sin(\theta) \cos(\theta) d\theta}{\int_0^{\pi/2} P_F(\theta) \sin^3(\theta) \cos(\theta) d\theta} \right]^{1/2} \quad (1)$$

où

$2W_0$ est le diamètre du champ de mode en μm ;

$P_F(\theta)$ est la distribution de l'intensité en champ lointain;

λ est la longueur d'onde de mesure, en μm ;

θ est l'angle dans la mesure en champ lointain à partir de l'axe de la fibre.

NOTE 1 Les limites d'intégration vont de zéro à $\pi/2$; il est cependant entendu que les intégrandes tendent vers zéro lorsque la variable d'intégration augmente, de sorte qu'en pratique, les intégrales peuvent être tronquées.

NOTE 2 P_F correspond à $F^2(\theta)$ dans les publications de l'UIT-T.

La méthode du champ lointain pour déterminer le diamètre du champ de mode d'une fibre unimodale est une procédure en deux étapes. La première étape consiste à mesurer le diagramme de rayonnement de la fibre en champ lointain. La seconde étape est une procédure mathématique fondée sur la définition de Petermann II du champ lointain pour calculer le champ de mode à partir des données en champ lointain, comme décrit dans la Formule (1) ci-dessus.

L'Annexe E fournit des données sur échantillon et des valeurs calculées pour les valeurs de $2W_0$ afin de pouvoir vérifier l'évaluation numérique de l'intégrale de Petermann II. Les données sur échantillon prennent la forme de la puissance symétrisée par moyennes des écarts, $P_F(\theta)$, fonction de l'angle, θ .

9.3 Méthode B – Ouverture variable en champ lointain

Les formules suivantes définissent le diamètre du champ de mode pour la méthode B concernant le champ électromagnétique émis à partir de l'extrémité de l'échantillon.

Calculer comme suit le diamètre du champ de mode, $2W_0$:

$$2W_0 = \left(\frac{\lambda}{\pi D} \right) \left[\int_0^{\infty} a(x) \frac{x}{(x^2 + D^2)^2} dx \right]^{-1/2} \quad (2)$$

où

$2W_0$ est le diamètre du champ de mode en μm ;

λ est la longueur d'onde de mesure, en μm ;

D est la distance entre l'ouverture et la fibre, en mm;

$a(x)$ est la fonction de transmission de l'ouverture complémentaire, calculée comme suit:

$$a(x) = 1 - \frac{P(x)}{P(\max)} \quad (3)$$

où

$P(x)$ est la puissance mesurée à travers une ouverture de rayon, x , ou de demi-angle, θ ;

$P(\max)$ est la puissance maximale, supposant une ouverture infinie;

x est le rayon d'ouverture, calculé comme suit:

$$x = D \tan(\theta) \quad (4)$$

Une autre expression équivalente de la Formule (2) est:

$$2W_0 = \frac{\lambda\sqrt{2}}{\pi} \left[\int_0^\infty a(\theta) \sin 2\theta d\theta \right]^{-1/2} \quad (5)$$

La méthode de l'ouverture variable en champ lointain pour calculer le diamètre du champ de mode d'une fibre unimodale est une procédure en deux étapes. La première étape consiste à mesurer la répartition bidimensionnelle en champ lointain comme étant la puissance passant à travers des ouvertures de différentes tailles. La seconde étape est une procédure mathématique qui consiste à calculer le diamètre du champ de mode à partir des données en champ lointain.

La base mathématique pour le calcul du diamètre du champ de mode est fondée sur la définition de Petermann II du champ lointain à partir de la Formule (1). La Formule (2) et la Formule (5) peuvent être tirées de la Formule (1) par intégration.

9.4 Méthode C – Exploration en champ proche

La formule suivante définit le diamètre du champ de mode pour la méthode C concernant le champ électromagnétique émis à partir de l'extrémité de l'échantillon.

Calculer le diamètre du champ de mode à partir du diagramme de rayonnement en champ proche mesuré, au moyen de l'intégrale suivante:

$$2W_0 = 2 \left(\frac{\int_0^\infty r f^2(r) dr}{\int_0^\infty r \left(\frac{df(r)}{dr} \right)^2 dr} \right)^{1/2} \quad (6)$$

où

$2W_0$ est le diamètre du champ de mode en μm ;

r est la coordonnée radiale, en μm ;

$f^2(r)$ est le diagramme de rayonnement en champ proche.

NOTE La limite d'intégration supérieure va jusqu'à l'infini; il est cependant entendu que, les intégrandes tendant vers zéro lorsque la variable d'intégration augmente, en pratique les intégrales peuvent être tronquées. Un algorithme de lissage peut être utilisé pour le calcul de la dérivée.

La méthode du champ proche pour déterminer le diamètre du champ de mode d'une fibre unimodale est une procédure en deux étapes. La première étape consiste à mesurer le diagramme de rayonnement de la fibre en champ proche. La seconde étape est une procédure mathématique qui consiste à calculer le diamètre du champ de mode à partir des données en champ proche.

La base mathématique du calcul du diamètre du champ de mode se fonde sur la définition de Petermann II à partir de la Formule (1). Le champ proche, $f(r)$, et le champ lointain, $F(\theta)$, forment une paire de transformées de Hankel. Par la transformation de Hankel et l'utilisation de $P_F = F^2(\theta)$, il est possible de déterminer la Formule (6) à partir de la Formule (1), et inversement.

10 Résultats

10.1 Informations disponibles pour chaque mesure

Consigner les informations suivantes pour chaque mesure:

- date et titre de la mesure,
- identification de l'échantillon,
- longueur d'onde de la source optique,
- diamètre(s) du champ de mode, en micromètres.

10.2 Informations disponibles sur demande

Les informations suivantes doivent être fournies sur demande:

- méthode de mesure utilisée: A, B, C ou D,
- type de source optique utilisée et largeur de raie spectrale (FWHM),
- description du dispositif,
- description du filtre des modes d'ordre supérieur,
- détails relatifs à la méthode de calcul,
- date du dernier étalonnage de l'équipement de mesure.

11 Informations à mentionner dans la spécification

La spécification particulière doit préciser les informations suivantes:

- type de fibre à mesurer,
- critères de refus ou d'acceptation,
- informations à consigner,
- toute divergence applicable par rapport à la procédure.

Annexe A (normative)

Exigences spécifiques à la méthode A – Diamètre du champ de mode par la technique de l’exploration directe en champ lointain

A.1 Appareillage

A.1.1 Généralités

L’Annexe A décrit l’appareillage en complément aux exigences de l’Article 6.

La Figure A.1 représente un montage typique pour mesure par exploration directe en champ lointain.

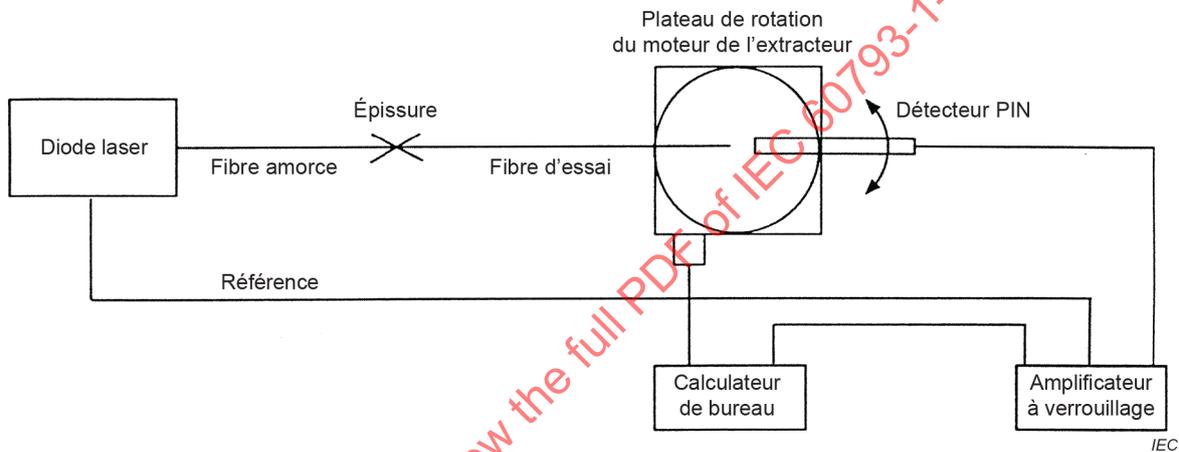


Figure A.1 – Montage de mesure en champ lointain

A.1.2 Ensemble détecteur à balayage – Système électronique de détection des signaux

Utiliser un mécanisme destiné à explorer la répartition des intensités en champ lointain. Utiliser un dispositif de balayage capable de fonctionner par échelons de 0,5° (ou des échelons encore plus fins) pour balayer le détecteur. Utiliser un dispositif d’alignement de l’axe de la fibre vis-à-vis du plan de rotation du détecteur, et d’alignement de la surface d’extrémité de la fibre avec le centre de rotation du balayage. Un système typique est susceptible de comporter une photodiode PIN, fonctionnant en mode photovoltaïque, amplifiée par un préamplificateur de courant, avec une détection synchrone assurée par un amplificateur à verrouillage. Il convient d’installer le détecteur à une distance d’au moins 10 mm de l’extrémité de la fibre (pour assurer le balayage du champ lointain par le détecteur), et il convient que la zone active du détecteur n’intercepte pas un angle trop important dans le champ lointain.

Pour cela, placer le détecteur à une distance d de l’extrémité de la fibre avec $d = K \times \frac{2wb}{\lambda}$

où

$2w$ est le diamètre du champ de mode attendu de l’échantillon;

b est le diamètre de la zone active du détecteur;

λ est la longueur d’onde;

K est le facteur de résolution dont la valeur est suffisamment grande pour empêcher la dégradation du balayage de champ lointain et son impact sur le calcul du diamètre du champ de mode.