

Effective area measurements of single-mode optical fibres — Guidance

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National foreword

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**RAPPORT
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unimodales –
Guide d'application**

**Effective area measurements of single-mode
optical fibres –
Guidance**



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**EFFECTIVE AREA MEASUREMENTS OF SINGLE-MODE OPTICAL FIBRES –
GUIDANCE**

FOREWORD

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IEC 62284, which is a technical report, has been prepared by subcommittee 86A: Fibres and cables, of IEC technical committee 86: Fibre optics.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86A/757/DTR	86A/799/RVC

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until 2004. At this date, the publication will be

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- withdrawn;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

EFFECTIVE AREA MEASUREMENTS OF SINGLE-MODE OPTICAL FIBRES – GUIDANCE

1 Scope and object

This technical report applies to single-mode optical fibres. Its object is to document the methods for measuring the effective area (A_{eff}) of these fibres.

It defines three methods of measuring A_{eff} . Information common to all the methods is found in the body of this document. Information specific to each method is found in the annexes. The three methods are:

- a) direct far-field (DFF)
- b) variable aperture in the far-field (VAMFF)
- c) near-field (NF)

The reference method, used to resolve disputes, is method A, direct far field.

Effective area is an optical attribute that is specified for single-mode fibres and used in system designs that may be affected by the non-linear refractive index coefficient, n_2 . There is agreement in both national and international standards bodies concerning the definition used in this technical report. Methods A, B, and C have been recognised as providing equivalent results, provided that good engineering is used in implementation.

The direct far-field is the reference method because it is the most direct method and is named as the reference method for mode field diameter in the ITU.

A mapping function is a formula by which the measured results of one attribute are used to predict the value of another attribute on a given fibre. For a given fibre type and design, the mode field diameter (MFD) (IEC 60793-1-45) can be used to predict the effective area with a mapping function. A mapping function is specific to a particular fibre type and design. Mapping functions are generated by doing an experiment in which a sample of fibre is chosen to represent the spectrum of values of MFD and in which the fibres in the sample are measured for both MFD and A_{eff} . Linear regression can be used to determine the fitting coefficient, k , as defined by the following:

$$A_{\text{eff}} = k\pi\left(\frac{\text{MFD}}{2}\right)^2 \quad (1)$$

NOTE Other mathematical models may be used if they are generally more accurate.

2 Reference documents

IEC 60793-1-45, *Optical fibres – Part 1-45: Measurement methods and test procedures – Mode field diameter*

ITU-T Recommendation G.650:2000, *Definition and test methods for the relevant parameters of single-mode fibres*

3 Apparatus

Annexes A, B, and C include schematics for each method.

3.1 Light source

Use a suitable coherent or non-coherent light source, such as a semiconductor laser or a sufficiently powerful filtered white light or LED source. The source should be stable in intensity and wavelength over a time period sufficient to perform the measurement. The wavelength of the source should be specified in the detail specification. Unless otherwise specified in the detail specification, the spectral line width should be less than or equal to 10 nm full width at half-maximum (FWHM).

3.2 Input optics

Use an optical lens system or fibre pigtail to excite the test fibre. Couple the power into the test fibre so it is insensitive to the position of the input end face. This can be done with a launch beam that spatially and angularly overfills the test fibre. If a butt splice is used, use index-matching fluid to avoid interference effects. The coupling should be stable for the duration of the test.

3.3 Cladding mode stripper

Use a device that extracts cladding modes. The fibre coating will typically perform this function.

3.4 High-order mode filter

Use a method to remove higher order modes whenever they are capable of propagating. For example, a one-turn bend of diameter ~ 30 mm in the test fibre is generally sufficient.

3.5 Computer

Optionally, use a computer to control the apparatus, take intensity measurements and compute the final result.

4 Sampling and specimens

4.1 Specimen length

Prepare the single-mode fibre test specimen to a length of, typically, $2,0 \text{ m} \pm 0,2 \text{ m}$.

4.2 Specimen end faces

Prepare flat end faces at the input and output ends of the specimen.

Poor output end quality can produce erroneous measurements.

5 Procedure

See Annexes A, B, or C for methods A, B, and C, respectively.

6 Calculation or interpretation of results

The following equations define the A_{eff} for the methods in terms of the electromagnetic field emitted from the end of the specimen. Calculation procedures are given in the annexes.

6.1 Near-field

Effective area, A_{eff} , is defined from the near-field intensity distribution, $I(r)$, r being the radial distance from the centre of the mode field profile, through the following equation:

$$A_{\text{eff}} = \frac{2\pi \left[\int_0^{\infty} I(r) r dr \right]^2}{\int_0^{\infty} I(r)^2 r dr} \quad (2)$$

6.2 Direct far-field

The zero-order Bessel function, J_0 , is used to determine the near-field intensity distribution pattern, $I(r)$, from the far-field power distribution, $P_{\text{ff}}(\theta)$:

$$I(r) = \left[\int (\pm) P_{\text{ff}}^{1/2}(\theta) J_0 \left(\frac{2\pi r \sin(\theta)}{\lambda} \right) \sin(\theta) d\theta \right]^2 \quad (3)$$

NOTE 1 The units of the measured wavelength, λ , should be the same as those of the radial co-ordinate, r . Typically these are measured in μm .

NOTE 2 If side lobes are observed, odd lobes are to be changed in sign (reference to $\pm$ sign in equation) before integration. (See Annex F for more information.)

The resultant near-field intensity distribution derived from equation (3) is then used with equation (2) to determine A_{eff} .

6.3 Variable aperture in the far-field

The power detected through an aperture of radius v is $P_v(v)$. The wavelength of light from the source is λ . The subtended half angle of the aperture is θ . The distance from the output end of the test fibre to the aperture is D . The direct far field power P_{ff} is related to the aperture power as:

$$\theta = \tan^{-1}\left(\frac{v}{D}\right) \quad (4a)$$

$$\text{Define } \rho = \frac{2\pi}{\lambda} \sin(\theta) \quad (4b)$$

$$P_{\text{ff}}(\rho) = \frac{dP_v(\rho)}{2\pi\rho d\rho} \quad (5)$$

Use equation (5) to convert $P_v(v)$ to $P_{\text{ff}}(\rho)$. Use equation (3) to convert to the near-field intensity pattern and then equation (2) to calculate the effective area.

7 Documentation

7.1 Information to be reported with each measurement

- a) Identification for each test specimen
- b) Effective area (A_{eff}), in squared micrometers (μm^2)
- c) Wavelength

7.2 Information that should be available upon request

- a) The measurement method used
- b) Description of the test equipment, including light sources, scanning or translation method, launch optics, cladding mode stripper, detection optics, and recording techniques
- c) Date and results for the most recent instrument calibration
- d) Data on measurement reproducibility

Annex A

Direct far-field method measurement specifics

A.0 Introduction

This annex documents the apparatus, procedure, and calculation for the direct far-field method.

Apparatus

A schematic of the apparatus is given in Figure A.1.

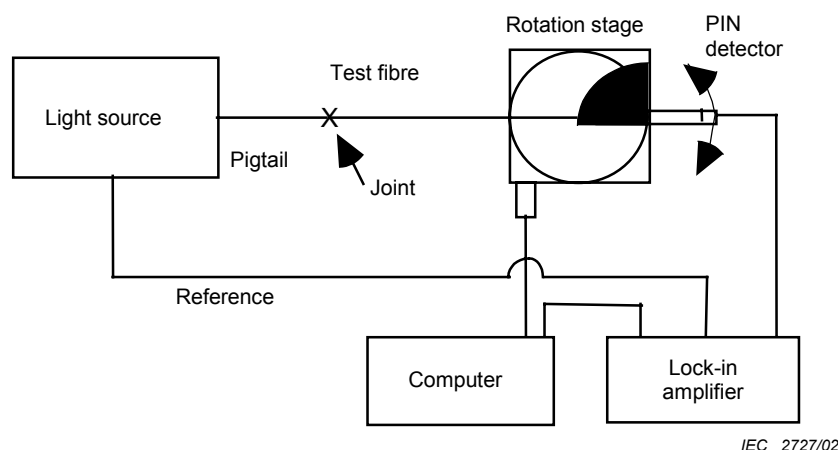


Figure A.1 – Test set-up for the direct far-field measurement

A.1.1 Detector and aperture

Use a detector, such as a PIN diode, that has enough dynamic range, that is, 50 dB down from the maximum power at zero degrees, and that is linear over the range of intensities that are encountered. The “detection floor” or “baseline noise” of the detector should be minimised so as to maximise the usable dynamic range of the system. A minimum of 50 dB of usable dynamic range is recommended. The detector should be placed a distance of at least $100 \frac{w^2}{\lambda}$ from the test fibre end face, where $2w$ is the nominal mode field diameter of the test fibre and λ is the nominal measurement wavelength. The angle subtended by the aperture in front of the detector should be less than or equal to $0,5^\circ$ in either dimension.

A.1.2 Scanning apparatus

Either scan the far-field radiation pattern by rotating the detector about an arc that is centred on the fibre end face or by rotating the fibre end face in front of a fixed detector. The scanning apparatus should be capable of steps of $0,5^\circ$ or finer. The scan should cover an entire diameter of the far-field pattern. Typically, the scanning apparatus should be capable of scanning an arc radius of at least $\pm 23,5^\circ$.

NOTE Multiple measurements, with the fibre rotated relative to the scanning plane will result in improved accuracy.

Procedure

- Prepare the test fibre
- Prepare the test fibre and align it in the system so the power on the centred detector (angle $\theta = 0$) is maximum
- Scan the detector
- Scan the detector over the arc radius specified in A.1.2, in increments of equal angle. For each position, θ_i , record the detected power, $P(\theta_i)$. The maximum detector angle used is $\theta_{\max}$ at index $i=n$, the number of positive angular positions. For $\theta < 0$, the index, i , is defined with negative values. Note: $\theta_0 = 0$.
- Complete the calculations
- Complete the calculations defined in Clause A.3 to determine the effective area

Calculations

The following calculations are one means of completing the integrations given in Clause 6. Other methods may be used if they are at least as accurate as the following. Instead of folding the data, for example, a separate mode field diameter calculation for positive and negative angular data sets can be completed and then averaged for the final result.

- Fold the far-field radiation power data

Let $P(\theta_i)$ be the measured power as a function of angular position, θ_i indexed by i . The folded power curve, $P_f(\theta_i)$, for $0 \leq \theta_i \leq \theta_{\max}$ is:

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

If the far-field data is not centred about $\theta = 0$, then the data around this point will cause errors to occur. The table below presents estimates of the error resulting from folding around $\theta=0$ of non-centred data.

Centre of symmetry error degrees	A_{eff} error μm^2
0	0,0 %
0,2	-0,4 %
0,4	-1,7 %

To avoid this folding error, the far-field data can be folded around the centroid of the far-field pattern.

Calculate the centroid of the peak region of the far-field data by the following equation:

$$\theta_{\text{centroid}} = \frac{\int_{\theta_{\text{left}}}^{\theta_{\text{right}}} \theta \cdot P(\theta_i) d\theta}{\int_{\theta_{\text{left}}}^{\theta_{\text{right}}} P(\theta_i) d\theta} \quad (\text{A.2})$$

where

θ_{left} is the angle that corresponds to the left-hand data point (negative θ) equal to 10 % of the peak power;

θ_{right} is the angle that corresponds to the right-hand data point (positive θ) equal to 10 % (−10 dB) of the peak power.

Numerical integration schemes described in A.3b) can be used.

The folded power curve, $P_{\text{fold}}(\theta_i)$, for $0 \leq \theta_i \leq \theta_{\text{max}}$

$$P_{\text{fold}}(\theta_i) = \frac{P_{\text{interp}}(\theta_{\text{centroid}} + i\Delta\theta) + P_{\text{interp}}(\theta_{\text{centroid}} - i\Delta\theta)}{2} \quad (\text{A.3})$$

where

P_{interp} is the cubic spline interpolation at the indicated angle;

$\Delta\theta$ is the angle step size of the originally measured data.

Alternatively, the far field profile can be separated into left and right sides, each processed independently to give two results, $A_{\text{eff left}}$ and $A_{\text{eff right}}$, with the average being reported. The left and right far field profiles can be defined by:

$$P_{\text{left}}(\theta_i) = P_{\text{interp}}(\theta_{\text{center}} - i\Delta\theta) \quad (\text{A.4a})$$

$$P_{\text{right}}(\theta_i) = P_{\text{interp}}(\theta_{\text{center}} + i\Delta\theta) \quad (\text{A.4b})$$

where θ_{center} is either $\theta=0$ (if folding about $\theta=0$) or θ_{centroid} (if folding about the centroid).

Also, the “as measured” data points can be used directly if the non-uniform step between θ_{centroid} and the first measured data point is taken into account in the subsequent integration steps.

b) Compute the near-field intensity pattern.

Use an appropriate numerical integration method to compute the integrals of equation (3). The following is an example. Any other integration method should be at least as accurate.

Calculate the near-field values for a range of radii, r_j , values ranging from zero to a value large enough that the computed intensity at the maximum radius is less than 0,01 % of the maximum intensity.

$$I(r_j) = \left[\sum_0^n (\pm) P_f^{1/2}(\theta_i) J_0 \left(\frac{2\pi r_j \sin(\theta_i)}{\lambda} \right) \sin(\theta_i) \Delta\theta \right]^2 \quad (\text{A.5})$$

where

$$\Delta\theta = \theta_1 - \theta_0;$$

n is the number of angles measured, determined by the number of iterations of $\Delta\theta$ to generate the largest angle where the measured power exceeds the detection floor of the system.

NOTE If side lobes are observed, odd lobes are changed in sign (reference to $\pm$ sign in equation) before integration. (See Annex F for more information.)

The error induced by using rectangular integration can be greatly reduced by using a higher order integration scheme such as an extended $1/N^3$ rule or Simpson's rule. The generalised forms are shown below for uniform step size h .

Extended $1/N^3$ rule:

$$\int_{x_1}^{x_n} f(x)dx = h \left[\frac{5}{12} f_1 + \frac{13}{12} f_2 + f_3 + f_4 + \dots + f_{n-2} + \frac{13}{12} f_{n-1} + \frac{5}{12} f_n \right] \quad (\text{A.6})$$

Simpson's rule:

$$\int_{x_1}^{x_n} f(x)dx = h \left[\frac{1}{3} f_1 + \frac{4}{3} f_2 + \frac{2}{3} f_3 + \frac{4}{3} f_4 + \dots + \frac{2}{3} f_{n-2} + \frac{4}{3} f_{n-1} + \frac{1}{3} f_n \right] \quad (\text{A.7})$$

c) Compute the integrals of equation (2).

Use an appropriate numerical integration method to compute the integrals of equation (2). The following is an example, assuming equally spaced measurement positions.

Any other integration method should be at least as accurate.

$$T = \left[\sum_0^m I(r_j) r_j \Delta r \right]^2 \quad (\text{A.8})$$

$$B = \sum_0^m I^2(r_j) r_j \Delta r \quad (\text{A.9})$$

where

$$\Delta r = r_1 - r_0;$$

m is the number of positions measured, determined by the radius at which the calculated near-field intensity is below 0,01 % (−20 dB) of the maximum near-field intensity power.

NOTE Caution should be taken when determining the maximum radius, r_m , since errors in the calculated near-field intensity at large radii tend to be quite significant. Using a maximum radius, r_m , corresponding to a near-field intensity of 0,01 % has been shown to produce A_{eff} values with error below 0,1 %. If r_m is chosen too large, then significant errors in the A_{eff} result can occur.

The error induced by using rectangular integration can be greatly reduced by using a higher order integration scheme such as an extended $1/N^3$ rule or Simpson's rule. See A.3b) for more details.

d) Complete the calculation:

$$A_{\text{eff}} = \frac{2\pi T}{B} \quad (\text{A.10})$$

Sample data and calculated values are provided in Annex D.