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Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 3-43: Examinations and measurements – Mode transfer function measurement for fibre optic sources

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The text of this standard is based on the following documents:

FDIS	Report on voting
86B/2780/FDIS	86B/2810/RVD

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

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FIBRE OPTIC INTERCONNECTING DEVICES
AND PASSIVE COMPONENTS –
BASIC TEST AND MEASUREMENT PROCEDURES –

Part 3-43: Examinations and measurements – Mode transfer function measurement for fibre optic sources

1 Scope

This part of IEC 61300 describes the method for measuring the mode transfer function (MTF) to be used in characterising the launch conditions for measurements of attenuation and or return loss of multimode passive components. The MTF may be measured at the operational wavelengths.

2 Normative references

The following referenced documents are indispensable for the application 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 61300-1, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 1: General and guidance*

IEC 61300-3-4, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 3-4: Examination and measurements – Attenuation*

IEC 60793-1-20, *Optical fibres – Part 1-20: Measurement methods and test procedures – Fibre geometry*

3 General description

The modal distribution launched into multimode fibre can vary widely with different light sources. This variation in launched modal distribution can result in significant differences in measured attenuation in the same component. The MTF test method gives information about the launched modal distribution (LMD) condition in a measured component. The MTF test method is based on a measurement of the near-field intensity distribution in the fibre [1], [2][1].

4 Theory

For a fibre with a power-law index profile $n(r)$, given by,

$$n(r) = n_1\left[1-2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]^{0,5} \quad \left(\frac{r}{a}\right) \leq 1 \tag{1}$$

where

a is the fibre core radius;

α is the profile factor (α = 2 for a parabolic profile);

---

[1] Figures in square brackets refer to the Bibliography.

Δ is the relative index difference, given by

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \tag{2}$$

where

n_1 is the index at fibre centre;

n_2 is the cladding index.

The near-field intensity profile in the fibre $I(r)$ may be determined from an integration of the mode transfer function $MTF(\delta)$ in the fibre, as follows (ignoring constants):

$$I(r) = \int_{\Delta\left(r/a\right)^{\alpha}}^{\Delta} MTF(\delta) \times d\delta \tag{3}$$

where

δ is the normalised propagation constant;

r/a is the normalised radial position.

Differentiating both sides gives the MTF as follows (ignoring constants):

$$MTF(\delta) = \left[\frac{dI(r)}{dr} \times \frac{1}{r^{\alpha-1}}\right]_{\delta=\Delta\left(r/a\right)^{\alpha}} \tag{4}$$

The MTF is usually plotted as in terms of the principal mode number m divided by the maximum principal mode number M, where

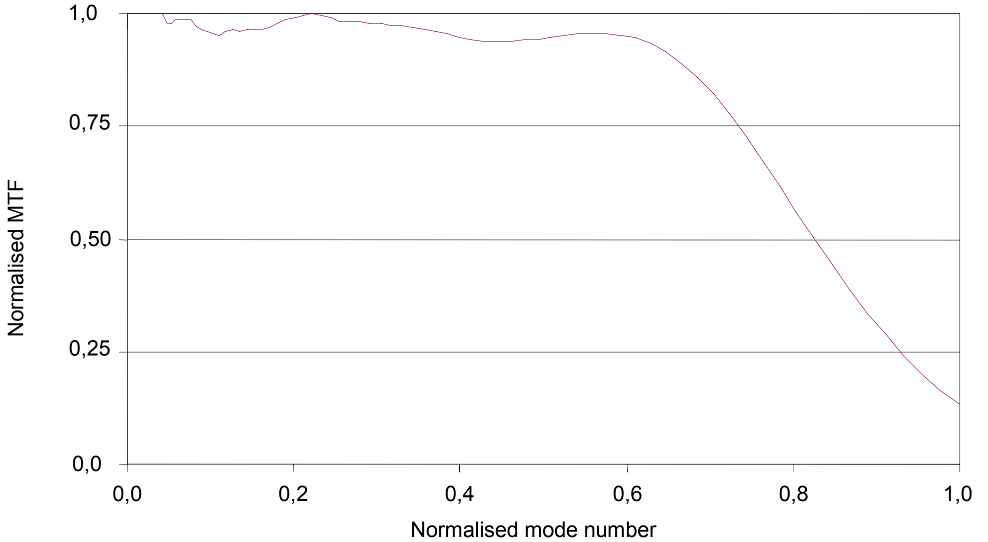
$$\frac{m}{M} = \left[\frac{\delta}{\Delta}\right]^{(2+\alpha)/2\alpha} = \left[\frac{r}{a}\right]^{(2+\alpha)/2} \tag{5}$$

The term (m/M) is usually referred to as the relative mode number, or the normalised mode number.

The maximum principle mode number M, is given by

$$M = \sqrt{\frac{\alpha}{\alpha+2}}\left(\frac{n_1 2\pi a}{\lambda}\right)\sqrt{\Delta} \tag{6}$$

A typical normalised MTF plot is shown in Figure 1, where it can be seen, in this example, that normalised mode numbers up to about 0,6 are equally filled and higher order modes are progressively less well-filled.



IEC 2371/08

Figure 1 – Example of normalised MTF

4.1 Alternative method

If the profile factor, α, in Equation (4) is not known, then an alternative expression for MTF can be used.

It is known[3] that in a fully-filled fibre (i.e. MTF=1 for all mode numbers) the near-field intensity profile, I_o, is approximately the same shape as the square of the refractive index profile, $n(r)^2$. Furthermore, the term $r^{\alpha-1}$ Equation (4) is equal (ignoring constants) to the differential of $n(r)^2$ and so Equation(4) can be rewritten as:

$$MTF(\delta) = \left[\frac{dI(r)}{dr} \times \frac{1}{dI_o(r)/dr} \right]_{\delta=\Delta\left(r/a\right)^2} \tag{7}$$

where a value of α=2 has been assumed in order to compute values for the normalised mode number.

Thus the MTF is equal to the ratio of the derivative of the intensity profile under test to the derivative of the intensity profile of the same fibre under fully-filled conditions.

4.2 Mode power distribution

For graded index multimode fibre the number of discrete modes in a particular mode group is proportional to the principal mode number. Thus higher-order mode groups contain more modes and therefore will carry more light if all the modes are equally excited. This can be represented by the mode power distribution (MPD), defined as:

$$MPD(m) = MTF(m) \times m \tag{8}$$

Because of this relationship of modes within mode groups, the MPD transform effectively displays the relative power in the mode groups.

An example of a normalised MPD is shown in Figure 2, where it can be seen, in this case, that the peak power level occurs around 0,65 normalised mode number.

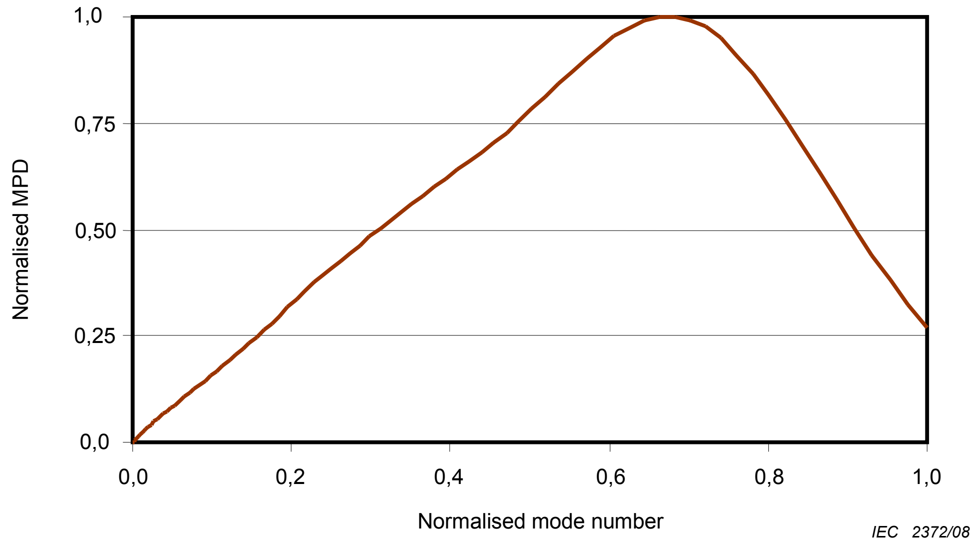


Figure 2 – Example of normalised MPD

4.3 Constraints

The MTF measurement method described herein is only valid under certain conditions, as follows:

- modes within a mode group carry the same power;
- there are random phases between the propagating modes.

It has been found[4] that both these conditions can be simultaneously met if the line-width $\Delta\lambda$ of the source is sufficiently broad, leading to the so-called "mode-continuum approximation", given by:

$$\frac{\Delta\lambda}{\lambda} \geq \frac{\sqrt{2\Delta}}{a \times k_0 \times N} \tag{10}$$

where

λ is the optical wavelength;

k_0 = $2\pi/\lambda$;

N is the group index, given by

$$N = n_1 - \lambda \times \frac{dn_1}{d\lambda} \tag{11}$$

Typically, for a 50 µm core diameter fibre, with 0,21 numerical aperture, then $\Delta\lambda$ > 0,5 nm at 850 nm and $\Delta\lambda$ > 1,0 nm at 1 300 nm satisfy this condition.

If the source line-width does not meet this criterion then interference between propagating modes may take place, resulting in "speckle" in the near-field image. The method can, however, still be applied to such sources by gently shaking, or somehow agitating, the fibre under test so as to cause a temporal averaging of the speckle pattern. In this case, it is important to ensure the near-field is azimuthally symmetric. This can be achieved by checking that the MTFs measured at 45° intervals around the fibre coincide with each other[5].

- The peak of the MPD occurs at a normalised mode number of <0,8.

It is known that deviation of the measured near-field intensity profile $I(r)$ from the power law profile in Equation (1), for fibres that are well-filled, may occur towards the core/cladding boundary. It is recommended that, in this case, the alternative method for the determination of MTF described in 4.1 is employed.

5 Apparatus

5.1 General

The apparatus is essentially a video microscope where a near-field image of the end of the fibre under test is formed on the surface of a camera by an optical system. The camera image is then digitised by a video digitiser and transferred to a computer for analysis and data presentation.

A schematic of a typical measurement configuration is shown in Figure 3.

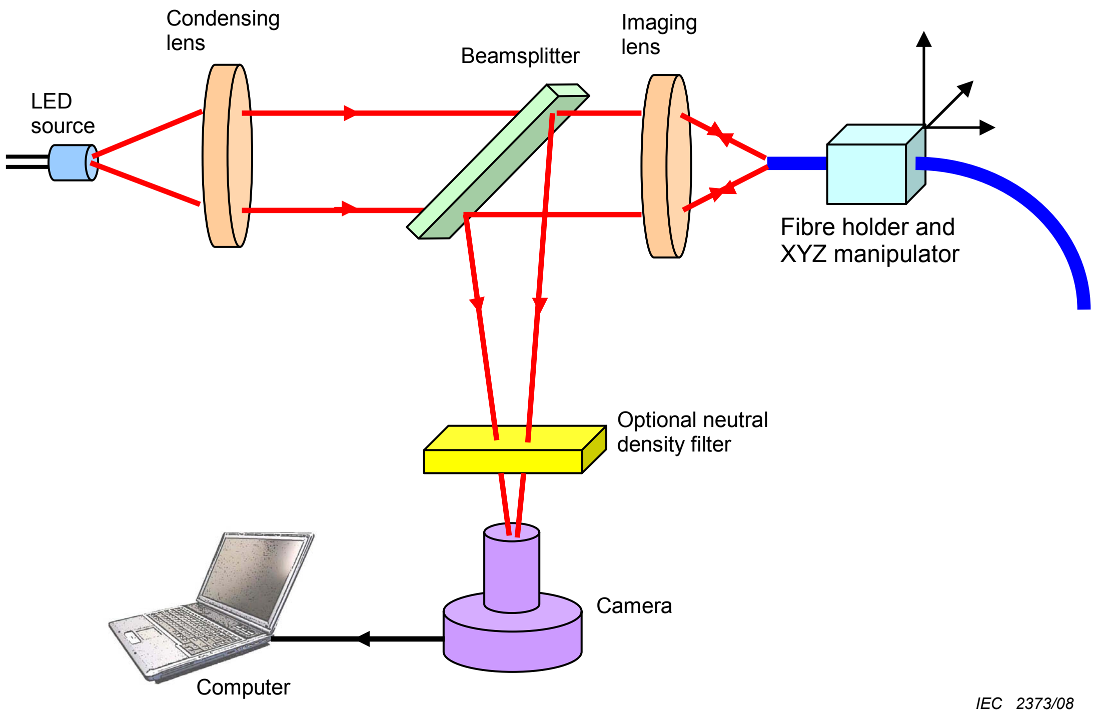


Figure 3 – Schematic of measurement apparatus

5.2 Test sample

The test sample consists of a multimode patch cord attached to a light source. It should be recognised that the mode distribution at the output of the patch cord is a product of both the launch conditions of the source and of the patch cord itself. The resultant MTF is therefore not a parameter of either the light source or the patch cord individually but rather of the combination, including the particular conditions under which the patch cord is disposed, such as bend radius.

5.3 Sample positioning device

A positioning device is required to ensure that the end of the patch cord under test is located on the optical axis of the instrument and also in the correct axial position to give a well-focussed image on the camera. For this purpose, an XYZ manipulation stage may be used or, preferably, a suitable connector receptacle mounted axially with the optics. An example is a standard 2,5 mm ferrule receptacle which is able to accommodate several connector types, such as FC, ST and SC. In this case, the XY positioning of the patch cord is well-defined and only a focussing adjustment is required.

5.4 Optical system

The optical system comprises magnifying optics to produce an image of the fibre end on the camera. To optimise measurement resolution, it is recommended that the optical magnification shall be chosen so that the image of the fibre core fills a reasonable proportion of the camera. Typically, this might be between 20 % and 50 % of the vertical extent of the camera.

The numerical aperture of the imaging system shall be greater than the numerical aperture of the fibre under test.

A means of illuminating the end face of the fibre in reflection may also be provided, such as a beam splitter and an LED source positioned between the focussing lens and the camera.

Neutral density (ND) filters may also be provided to control the amount of light reaching the camera.

5.5 Camera

A high quality camera shall be used that has demonstrable geometrical uniformity and intensity linearity. The pixel size of the camera, $picsize$, shall be sufficiently small compared with the magnified near-field image as to be less than the system diffraction limits by a factor of 2, given by

$$Picsize < \frac{0{,}61 Mag\lambda}{2NA} \tag{12}$$

where

Mag is the system magnification;

NA is the numerical aperture of the fibre.

For example, if Mag = 20, NA = 0,21, λ = 850 nm then $picsize$ < 24 µm. It is recommended, however, that the camera pixel size is much smaller than this. In this example, the corresponding pixel size at the fibre would be equal to $picsize$ divided by Mag, which is equal to 1,2 µm.

5.6 Video digitiser

The video digitiser, which is connected to the camera, provides the computer with a digitised image of the fibre end. A typical video digitiser will provide an 8 bit image, although a digitiser providing more bits, for example 12, may be used for increased resolution.

5.7 Calibration

The calibration factor is expressed in units of µm/pixel. It is required in 7.4 to convert the processed data between pixel space and µm units.

The optical system may be calibrated by measuring an artefact of known dimension, such as a microscope graticule or an optical fibre of known cladding diameter. The calibration artefact is positioned in the object plane of the system and focussed onto the camera. In the case of a graticule, illumination may be by transmitted or reflected light. In the case of an optical fibre, reflected light must be used. This is typically achieved by the use of a light source and beam splitter positioned in the optical system between the focussing lens and the camera.

NOTE The wavelength of the illumination source should be within 30 nm of the nominal wavelength of the source under test so as to minimise chromatic effects on the system magnification.

Measure the size of the calibration artefact in pixels, n_{pix}. If the size of the artefact in µm is n_{cal}, then the calibration factor, $calfactor$, is given by

$$Calfactor = \frac{n_{cal}}{n_{pix}} \tag{13}$$

The system magnification, Mag, which is required in 5.5 may be calculated from the calibration factor as follows:

$$Mag = \frac{picsize}{calfactor} \tag{14}$$

NOTE In the case where the camera pixels are non-square, then the calibration factor must be determined along the particular axis of the camera that is used for subsequent MTF measurements, (see Clause 7).

6 Procedure

6.1 Mounting and aligning the sample

Mount the fibre to be measured in the sample positioning device in the object plane of the optical system and switch on the end illumination source. Align the lateral position of the fibre end, if necessary, and adjust the focus position of the fibre to give a well-focussed near-field image on the camera. Switch off the end illumination and switch on the source under test, which, if necessary, should be allowed to stabilise.

6.2 Optimisation

In order to utilise the full analogue-to-digital converter (ADC) range of the video digitiser effectively adjust the intensity of the image so that it fills typically about 90 % of the ADC range. This may be achieved by any or a combination of the following means:

- adjusting the intensity of the light source;
- the use of neutral density (ND) filters in front of the camera;
- adjusting the gain and/or electronic shuttering of the camera.

6.3 Acquiring the data

A digitised image of the fibre end is then transferred by the controlling computer for analysis. Typically the image is then converted to a two-dimensional array of ADC values for subsequent processing. In order to improve signal-to-noise ratio, several images or frames, can be serially acquired and their ADC values averaged on a pixel-by-pixel basis. A typical number of frames is ten to twenty, although, in the case of a coherent source where agitation must be used to break up the speckle pattern, several hundred frames is typical.

If the alternative method (4.1) is being used then it is necessary to disconnect the source under test from the patchcord and replace this with a source which overfills the patchcord. A second digitised image is then obtained in the same manner as above.

7 Calculations

7.1 Background level subtraction

It is important that the background level, or dark level, of the camera is uniform to avoid unwanted noise caused by the differential in Equation (4). The background uniformity may be improved by acquiring image data with the light source turned off and then subtracting this on a pixel-by-pixel basis from the measured fibre image.

7.2 Location of centroid of intensity profile

The centroid, or centre of gravity, of the near-field image is required so that an intensity profile through the fibre centre can be extracted. To do this, only the vertical centroid is required. A typical method is as follows:

a) locate the co-ordinates of the position of peak power in the image;

b) extract a 2-D matrix of pixels, I_{core}, from the acquired, background-subtracted image, centred on the position of peak. The first index of I_{core} is the row index (y-dimension) whose extent is rows. The second index of I_{core} is the column index (x-dimension) whose extent is cols. I_{core} shall contain the entire core image although effort should be made to limit the dark pixels since they contribute only noise to the following computations;

c) compute the sum of the intensity values along each row in I_{core}, $sumrow$(i), yielding a 1D array of sums. This is called collapsing the 2D data onto the Y axis:

$$Sumrow(i) = \sum_{j=1}^{cols} Icore(i,j) \qquad (15)$$

d) compute the sum of the elements of the array of sums, yielding a single scalar number, $sumofsums$;

$$Sumofsums = \sum_{i=1}^{rows} sumrow(i) \qquad (16)$$

e) compute the product of each element of the array of sums with its array co-ordinate and sum these products to yield a single scalar number, $sumproduct$;

$$Sumproduct = \sum_{i=1}^{rows} sumrow(i) \times i \qquad (17)$$

f) the centroid, in pixel units, is then given by the sum of the products divided by the sum of the sums:

$$Centroid = \frac{sumproduct}{sumofsums} \qquad (18)$$

g) the intensity profile, $I(i)$, along the row that is nearest to the centroid is then extracted for analysis. Note that, for cameras meeting the requirements of Equation (12), the error in this approximation is negligible.

7.3 Differentiating the intensity profile

The next step is to differentiate the near-field intensity profile, as required by Equation (4). Any suitable numerical method can be used but a recommended method is that of the Savitsky-Golay filter[6]. This filter effectively fits a sliding polynomial across the data-set and computes the differential from the fitted coefficients. One such polynomial is that of a quadratic. A required parameter is the number of data-points over which the polynomial is fitted, known as the fit-window. Typically, the wider the fit-window the greater the data smoothing that occurs, similar to a low-pass filter. A trade-off exists, therefore between the level of noise in the differentiated data and amount of detail that is lost by the smoothing process.

The intensity profile that was extracted in 7.2 extends well beyond the extent of the fibre core. However, the MTF is only defined between the fibre centre and the edge of the core so the end points need to be defined. The fibre centre is located from the differentiated data as follows:

a) locate the approximate centre of the fibre by computing the mean pixel position, Xc, of the positions corresponding to the maximum and minimum values of the differentiated data-set, $Idiff(i)$;

b) compute the symmetry function, $Sym(k)$, about this position, as follows:

$$Sym(k) = \sum_{i=Xc-nsym}^{k-1} \left| Idiff(i) \times |k-i| \right| + \sum_{i=k+1}^{Xc+nsym} \left| Idiff(i) \times |k-i| \right| \tag{19}$$

where

$nsym$	is the width of window for the symmetry computation, typically similar to the core radius, in pixels;
k	takes integer values from (Xc-$nsym$) to (Xc+$nsym$).

c) locate the pixel nearest to the minimum of $Sym(k)$. This corresponds to the fibre centre.

An example of a computed symmetry function for a particular intensity profile is shown in Figure 4, where the position of maximum symmetry, corresponding to the minimum of the symmetry, zeropos, corresponding to the minimum of the symmetry function, is indicated.

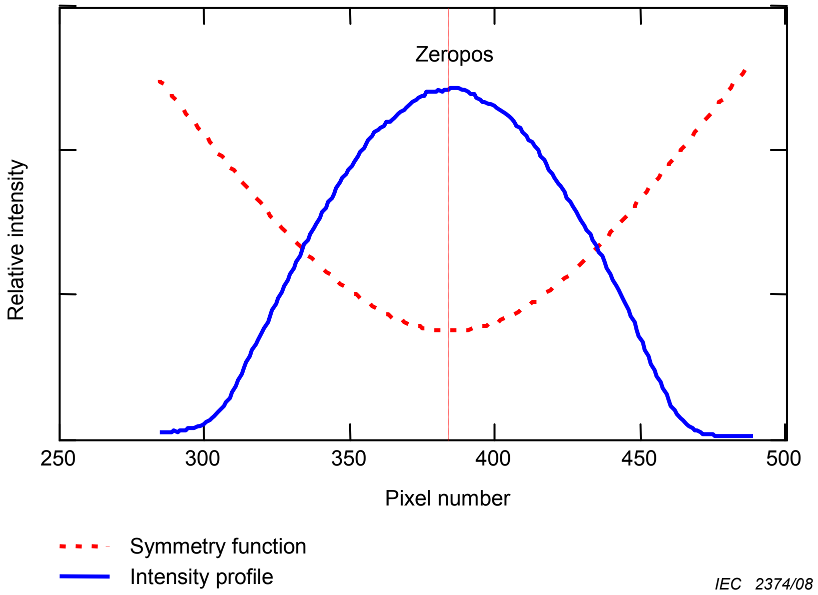


Figure 4 – Location of fibre centre using symmetry computation

Next, in order to compute the MTF, separate the differentiated data-set into two halves, left and right, about the computed fibre centre and average these together on a pixel-by-pixel basis.

For diagnostic purposes, the MTF may also be independently computed for both the left and right halves of the differentiated data-set. Comparison of the resulting curves provides a useful check of the requirement for azimuthal symmetry (4.3). Differences between the two curves may indicate, for example, that part of the fibre end is scratched or contaminated.

7.4 Computing the MTF

The final step is to divide the differential, $dI(r)/dr$, by the factor ($r^{\alpha-1}$), in pixel space, shown in Equation (4) and reproduced below as a function of the principal mode number:

$$MTF(m) = \left[\frac{dI(r)}{dr} \times \frac{1}{r^{\alpha-1}} \right]_{m=M\left[\frac{r}{a}\right]^{(2+\alpha)/2}} \tag{20}$$

The MTF is then normalised and plotted as a function of normalised mode number, given by Equation(5) as:

$$\frac{m}{M} = \left[\frac{r}{a}\right]^{(2+\alpha)/2} \tag{21}$$

where in Equation (21) the fibre core radius, a, is replaced by the number of pixels corresponding to the fibre core radius, $pixrad$:

$$Pixrad = \frac{a}{calfactor} \tag{22}$$

where calfactor is the calibration factor of the optical system, described in 5.7, and expressed in units of µm/pixel.

NOTE If the fibre core radius is unknown, then it may be determined according to the procedures given in IEC 60793-1-20.

If the alternative method is being used (see 4.1) then the reference image obtained in 6.3 is processed in the same way as described in 7.1 to 7.3. The MTF is computed, in pixel space, according to Equation (7), which is reproduced below as a function of the principal mode number:

$$MTF(m) = \left[\frac{dI(r)}{dr} \times \frac{1}{dI_o(r)/dr} \right]_{m=M\left[\frac{r}{a}\right]^{2}} \tag{23}$$

The MTF is then normalised and plotted as a function of the normalised mode number, given by:

$$\frac{m}{M} = \left[\frac{r}{a}\right]^{2} \tag{24}$$

where in Equation (24) the fibre core radius, a, is replaced by the number of pixels corresponding to the fibre core radius, pixrad, defined in Equation (22).

NOTE For display purposes, data points for a normalised mode number below 0,05 may be ignored in the normalisation and values greater than 1 in this region may not be plotted. Additionally, negative values may be omitted from the plot.

8 Results

The following information shall be provided with each measurement:

- date and title of measurement;
- identification of test method (this document);
- identification and description of specimen, including light source and patch cord;
- the test wavelength;
- the fit-window used in differentiating the profile intensity data, in µm;

- the number of frames averaged;
- the normalised mode transfer function (MTF);
- the normalised mode power distribution (MPD);

The following information may also be provided if required:

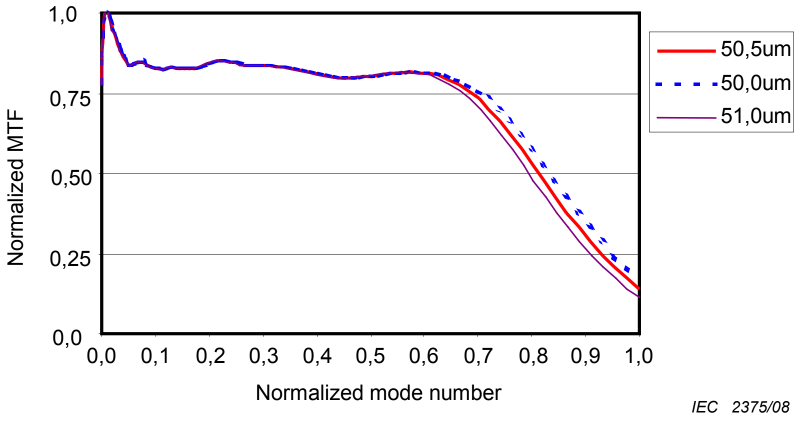
- the near-field image (bitmap).

Annex A
(informative)

Sensitivity of MTF and MPD to core parameters

The measurement of the modal distribution according to Equation (4) depends on a knowledge of the fibre core radius and the index profile factor.

Examples of the effect on the MTF and MPD of entering different core diameters into Equation (4) are shown in Figure A.1



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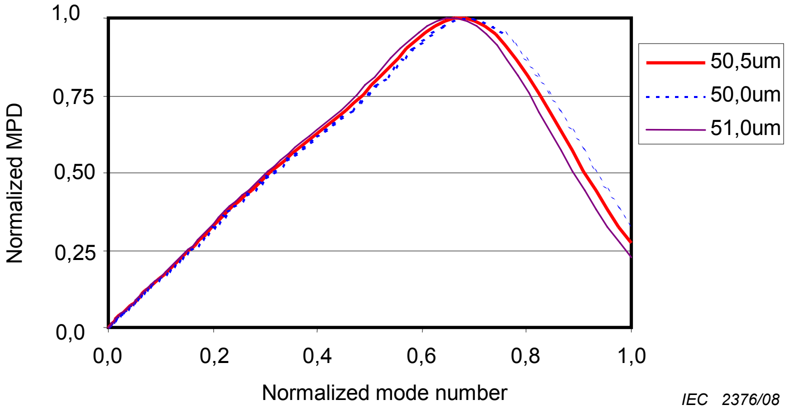
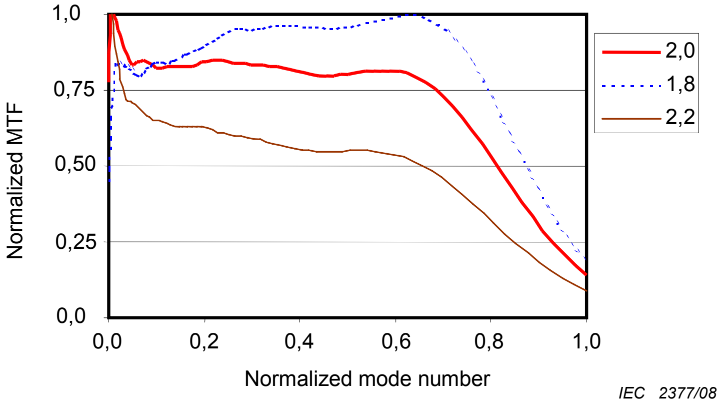


IEC 2376/08

Figure A.1 – Sensitivity of MTF and MPD to core diameter

Examples of the effect on the MTF and MPD of entering different profile factors, α, into Equation (4) are shown in Figure A.2



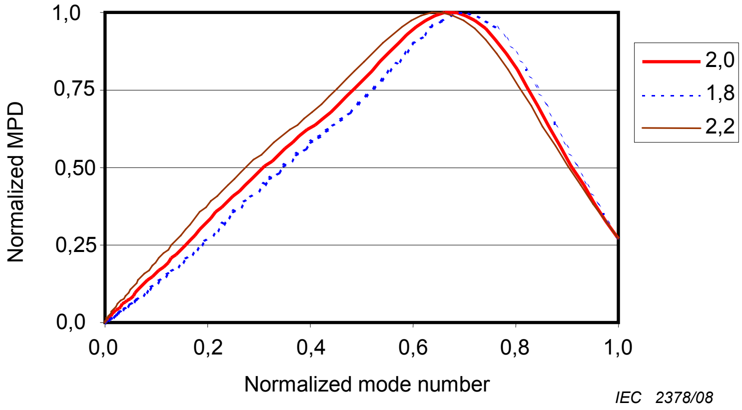


Figure A.2 – Sensitivity of MTF and MPD to profile factor

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