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IEC PAS 61300-3-43

Pre-Standard

First edition
2006-02

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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**Fibre optic interconnecting devices and passive components –
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Examinations and measurements –
Mode transfer function measurement
for fibre optic sources**

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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 PAS is based on the following document:	This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document:
Draft PAS	**Report on voting**
86B/2199/NP	86B/2257/RVN

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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 characterizing the launch conditions for measurements of attenuation and or return loss of multimode passive components, according to IEC 61300-1 and IEC 61300-3-4. 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*

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

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

where
a is the fibre core radius;
α is the profile factor (α = 2 for a parabolic profile);
Δ is the relative index difference, given by

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

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \qquad (2)$$

where

n_1 is the index at the 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, δ, in the fibre, as follows (ignoring constants):

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

where

δ is the normalized propagation constant;

r/a is the normalized radial position.

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

$$MTF(\delta) = \left[\frac{\mathrm{d}I(r)}{\mathrm{d}r}\cdot\frac{1}{r^{\alpha-1}}\right]_{\delta=\Delta\left(r/a\right)^{\alpha}} \qquad (4)$$

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

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

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

The maximum principle mode number, M, is given by

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

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

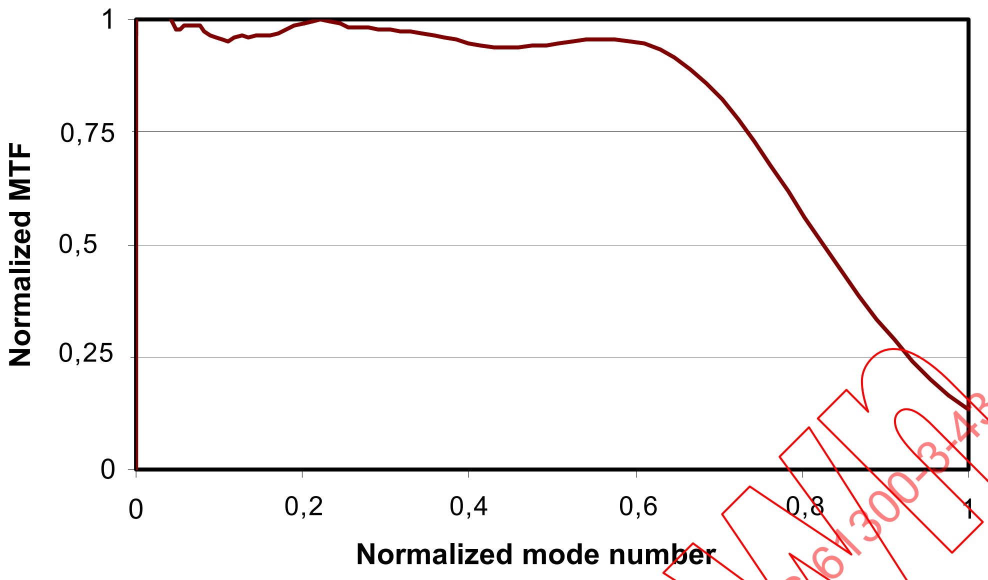

Figure 1 – Example of normalized MTF

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 the same shape as the square of the refractive index profile, $n(r)^2$. Furthermore, the term $r^{\alpha-1}$ in equation (4) is equal (ignoring constants) to the differential of $n(r)^2$ and so equation (4) can be rewritten as:

$$MTF(\delta) = \left[\frac{\mathrm{d}I(r)}{\mathrm{d}r} \cdot \frac{1}{\mathrm{d}I_o(r)/\mathrm{d}r} \right]_{\delta=\Delta\left(r/a\right)^2} \quad (7)$$

where a value of α = 2 has been assumed in order to compute values for the normalized 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 MPD, defined as:

$$MPD(m) = MTF(m) \cdot m \quad (8)$$

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

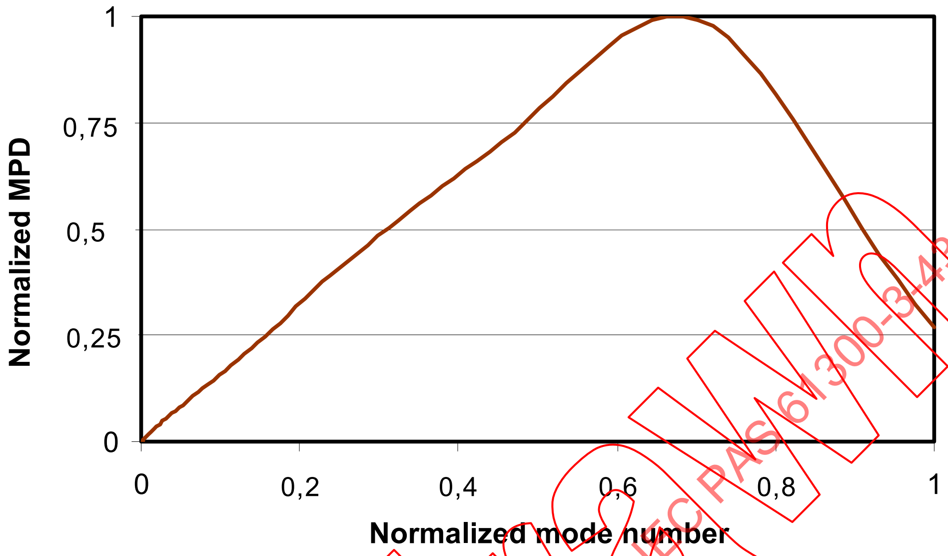

Figure 2 – Example of normalized MPD

4.3 Relative power distribution

The relative power distribution (RPD) is another way of expressing MTF data. It is defined as:

$$RPD(\mu) = \int_{\mu}^{1} MTF(m) \cdot \mathrm{d}m \qquad (9)$$

where μ is a variable principle mode number, required for the integration, that takes on values from 1 to 0 (m is the principle mode number).

The RPD represents the area under the MTF curve as the mode number is progressively reduced from unity and is, therefore, a measure of the cumulative distribution of power starting at the highest mode number.

An example of a normalized RPD is shown in Figure 3.

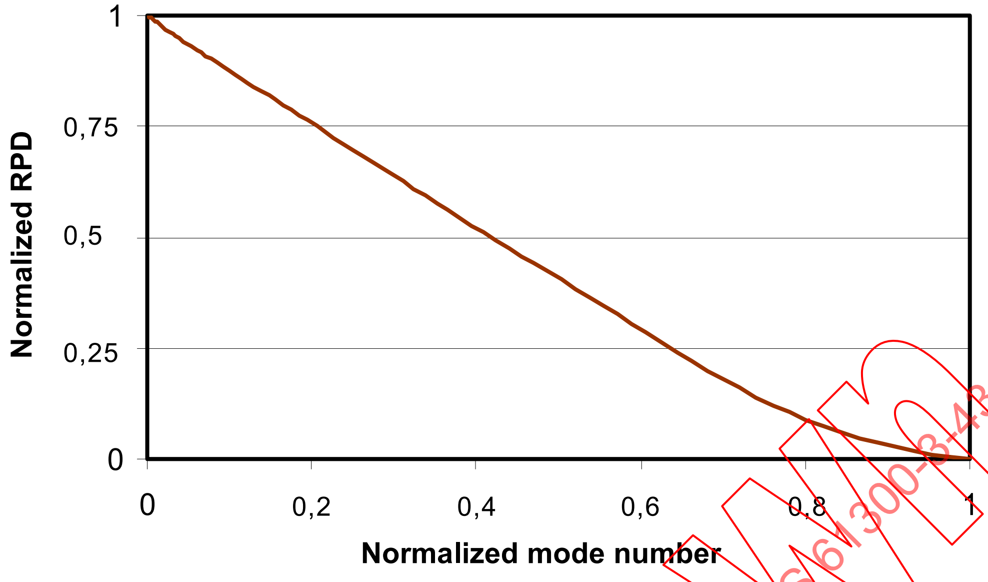

Figure 3 – Example of normalized RPD

4.4 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 simultaneously be met if the line-width $\Delta\lambda$ of the source is sufficiently broad, leading to the so-called “mode-continuum approximation”, given by:

$$\frac{\Delta\lambda}{\lambda} \geq \frac{\sqrt{2\Delta}}{a \cdot k_o \cdot N} \tag{10}$$

where

λ is the optical wavelength;

k_0 is $2\pi/\lambda$;

N is the group index, given by:

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

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].

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 camera, such as a CCD or CMOS camera, by an optical system. The camera image is then digitized by a video digitizer and transferred to a computer for analysis and data presentation.

5.2 Test sample

The test sample consists of a multimode patch cord attached to a light source. It should be recognized 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-focused 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 focusing 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 optimize measurement resolution, it is recommended that the optical magnification 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 focusing 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 having demonstrable geometrical uniformity and intensity linearity shall be used. 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:

$$picsize < \frac{0{,}61 Mag \lambda}{2NA} \qquad (12)$$

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 the picsize is <24 μm. It is recommended, however, that the camera pixel size is much smaller 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 digitizer

The video digitizer which is connected to the camera provides the computer with a digitized image of the fibre end. A typical video digitizer will provide an 8-bit image, although a digitizer 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 the pixel space and the 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 focused 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 focusing lens and the camera.

NOTE The wavelength of the illumination source shall be within 30 nm of the nominal wavelength of the source under test so as to minimize 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:

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

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-focused 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 stabilize.

6.2 Optimisation

In order to utilize the full analogue-to-digital converter (ADC) range of the video digitizer, the intensity of the image should be effectively adjusted 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;
- 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 digitized 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 10 to 20, 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 patch cord and replace this with a source which overfills the patch cord. A second digitized 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 the centroid of the 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 coordinates 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 the I_{core} is the row index (y-dimension) whose extent is rows. The second index of the I_{core} is the column index (x-dimension) whose extent is cols. The I_{core} shall contain the entire core image although an 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.

$$sumrow(i) = \sum_{j=1}^{cols} I_{\text{core}}(i,j) \quad (15)$$

(d) Compute the sum of the elements of the array of sums, yielding a single scalar number, sumofsums.

$$sumofsums = \sum_{i=1}^{rows} sumrow(i) \quad (16)$$

(e) Compute the product of each element of the array of sums with its array coordinate and sum these products to yield a single scalar number, sumproduct

$$sumproduct = \sum_{i=1}^{rows} sumrow(i) \cdot i \quad (17)$$

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

$$centroid = \frac{sumproduct}{sumofsums} \tag{18}$$

(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 the 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, X_c, of the positions corresponding to the maximum and minimum values of the differentiated data-set, $I_{diff(i)}$).

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

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

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 function, is indicated.

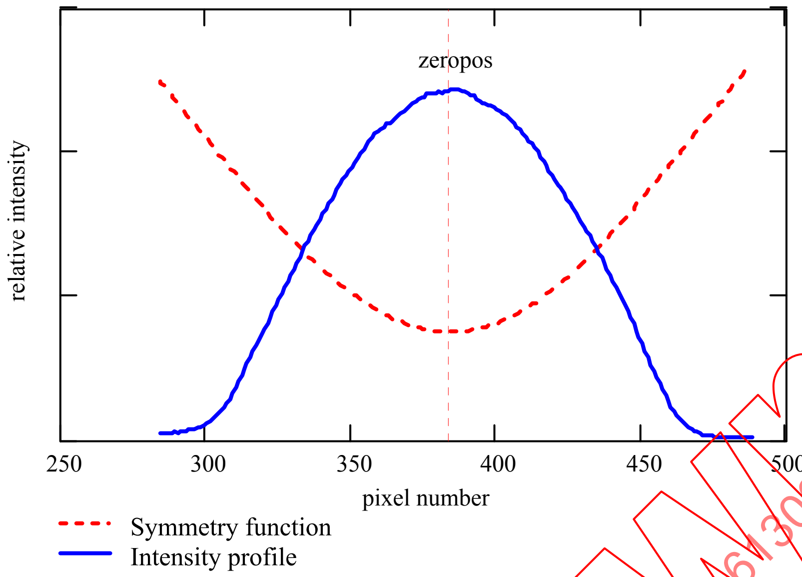

Figure 4 – Location of fibre centre using symmetry computation

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 (4.4). 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, $\mathrm{d}I(r)/\mathrm{d}r$, by the factor ($r^{\alpha-1}$), in pixel space, shown in equation (4) and reproduced below as a function of the principal mode number:

$$MTF(m) = \left[\frac{\mathrm{d}I(r)}{\mathrm{d}r} \cdot \frac{1}{r^{\alpha-1}}\right]_{m=M\left[\frac{r}{a}\right]^{(2+\alpha)/2}} \qquad (20)$$

The MTF is then normalized and plotted as a function of the normalized mode number, given by equation(5) as:

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

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

$$pixrad = \frac{a}{calfactor} \qquad (22)$$

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

If the alternative method is being used (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:

$$MTF(m) = \left[\frac{\mathrm{d}I(r)}{\mathrm{d}r} \cdot \frac{1}{\mathrm{d}I_o(r)/\mathrm{d}r}\right]_{m=M\left[\frac{r}{a}\right]^2} \qquad (23)$$

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

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

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 normalized mode number below 0,05 may be ignored in the normalization 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;
– test wavelength;
– fit-window used in differentiating the profile intensity data, in μm;
– number of frames averaged;
– normalized MTF;
– normalized MPD.

The following information may also be provided if required:

– near-field image (bitmap)
– normalized RPD.