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Recommendation G.652

CHARACTERISTICS OF A SINGLE-MODE OPTICAL FIBRE CABLE

(Malaga-Torremolinos, 1984; amended at Melbourne, 1988)

The CCITT,

considering

(a) that single-mode optical fibre cables are widely used in telecommunication networks;

(b) that the foreseen potential applications may require several kinds of single-mode fibres differing in:

— geometrical characteristics;

— operating wavelength;

— attenuation dispersion, cut-off wavelength, and other optical characteristics;

— mechanical and environmental aspects;

(c) that recommendations on different kinds of single-mode fibres can be prepared when practical use studies have sufficiently progressed,

recommends

a single-mode fibre which has the zero-dispersion wavelength around 1300 nm and which is optimized for use in the 1300 nm wavelength region, and which can also be used in the 1550 nm wavelength region (where this fibre is not optimized).

This fibre can be used for analogue and for digital transmission.

The geometrical, optical and transmission characteristics of this fibre are described below, together with applicable test methods.

The meaning of the terms used in this Recommendation is given in Annex A and the guidelines to be followed in the measurements to verify the various characteristics are indicated in Annex B. Annexes A and B may become separate Recommendations as additional single-mode fibre Recommendations are agreed upon.

1 Fibre characteristics

Only those characteristics of the fibre providing a minimum essential design framework for fibre manufacture are recommended in § 1. Of these, the cable fibre cut-off wavelength may be significantly affected by cable manufacture or installation. Otherwise, the recommended characteristics will apply equally to individual fibres, fibres incorporated into a cable wound on a drum, and fibres in installed cable.

This Recommendation applies to fibres having a nominally circular mode field.

1.1 *Mode field diameter*

The nominal value of the mode field diameter at 1300 nm shall lie within the range 9 to 10 µm. The mode field diameter deviation should not exceed the limits of ±10% of the nominal value.

Note 1 — A value of 10 µm is commonly employed for matched cladding designs, and a value of 9 µm is commonly employed for depressed cladding designs. However, the choice of a specific value within the above range is not necessarily associated with a specific fibre design.

Note 2 — It should be noted that the fibre performance required for any given application is a function of essential fibre and systems parameters, i.e., mode field diameters, cut-off wavelength, total dispersion, systems operating wavelength, and bit rate/frequency of operation, and not primarily of the fibre design.

Note 3 — The mean value of the mode field diameter, in fact, may differ from the above nominal values provided that all fibres fall within ±10% of the specified nominal value.

1.2 *Cladding diameter*

The recommended nominal value of the cladding diameter is 125 µm. The cladding deviation should not exceed the limits of ± | .4%.

For some particular jointing techniques and joint loss requirements, other tolerances may be appropriate.

1.3 *Mode field concentricity error*

The recommended mode field concentricity error at 1300 nm should not exceed 1 µm.

Note 1 — For some particular jointing techniques and joint loss requirements, tolerances up to 3 µm may be appropriate.

Note 2 — The mode field concentricity error and the concentricity error of the core represented by the transmitted illumination using wavelengths different from 1300 nm (including white light) are equivalent. In general, the deviation of the centre of the refractive index profile and the cladding axis also represents the mode field concentricity error but, if any inconsistency appears between the mode field concentricity error, measured according to the reference test method (RTM), and the core concentricity error, the former will constitute the reference.

1.4 *Non-circularity*

1.4.1 *Mode field non-circularity*

In practice, the mode field non-circularity of fibres having nominally circular mode fields is found to be sufficiently low that propagation and jointing are not affected. It is therefore not considered necessary to recommend a particular value for the mode field non-circularity. It is not normally necessary to measure the mode field non-circularity for acceptance purposes.

1.4.2 *Cladding non-circularity*

The cladding non-circularity should be less than 2%. For some particular jointing techniques and joint loss requirements, other tolerances may be appropriate.

1.5 *Cut-off wavelength*

Two useful types of cut-off wavelengths can be distinguished:

a) the cut-off wavelength λ_c | of a primary coated fibre according to the relevant fibre RTM;

b) the cut-off wavelength $\lambda_{c\backslash \mathrm{d}c}$ | of a cabled fiber in a deployment condition according to the relevant cable RTM.

The correlation of the measured values of λ_c | and $\lambda_{c\backslash \mathrm{d}c}$ | epends on the specific fibre and cable design and the test conditions. While in general $\lambda_{c\backslash \mathrm{d}c} < \lambda_c$, a quantitative relationship cannot easily be established. The importance of ensuring single-mode transmission in the minimum cable length between joints at the minimum system operating wavelength is paramount. This can be approached in two alternate ways:

1) recommending λ_c | to be less than 1280 nm; when a lower limit is appropriate, λ_c should be greater than 1100 nm;

2) recommending λ_{cc} | to be less than 1270 nm.

Note — A sufficient wavelength margin should be assured between the lowest-permissible system operating wavelength λ_s of 1270 nm, and the highest-permissible cable cut-off wavelength λ_{cc}. Several Administrations favour a maximum λ_{cc} of 1260 nm to allow for fibre sampling variations and source wavelength variations due to tolerance, temperature, and ageing effects.

These two specifications need not both be invoked; users may choose to specify λ_c or λ_{cc} according to their specific needs and the particular envisaged applications. In the latter case, it should be understood that λ_c may exceed 1280 nm.

In the case where the user chooses to specify λ_c as in 1), then $\lambda_{c\backslash dc}$ need not be measured.

In the case where the user chooses to specify $\lambda_{c\backslash dc}$, it may be permitted that λ_c be higher than the minimum system operating wavelength, relying on the effects of cable fabrication and installation to yield $\lambda_{c\backslash dc}$ values below the minimum system operating wavelength for the shortest length of cable between two joints.

In the case where the user chooses to specify $\lambda_{c\backslash dc}$, a qualification test may be sufficient to verify that the $\lambda_{c\backslash dc}$ requirement is being met.

1.6 *1550 nm loss performance*

In order to ensure low-loss operation of deployed 1300 nm-optimized fibres in the 1550 nm wavelength region, the loss increase of 100 turns of fibre loosely-wound with a 37.5 mm radius, and measured at 1550 nm, shall be less than 1.0 dB.

Note 1 — A qualification test may be sufficient to ensure that this requirement is being met.

Note 2 — The above value of 100 turns corresponds to the approximate number of turns deployed in all splice cases of a typical repeater span. The radius of 37.5 mm is equivalent to the minimum bend-radius widely accepted for long-term deployment of fibres in practical systems installations to avoid static-fatigue failure.

Note 3 — If for practical reasons fewer than 100 turns are chosen to implement this test, it is suggested that not less than 40 turns, and a proportionately smaller loss increase be used.

Note 4 — If bending radii smaller than 37.5 mm are planned to be used in splice cases or elsewhere in the system (for example, R = 30 mm), it is suggested that the same loss value of 1.0 dB shall apply to 100 turns of fibre deployed with this smaller radius.

Note 5 — The 1550 nm bend-loss recommendation relates to the deployment of fibres in practical single-mode fibre installations. The influence of the stranding-related bending radii of cabled single-mode fibres on the loss performance is included in the loss specification of the cabled fibre.

Note 6 — In the event that routine tests are required a small diameter loop with one or several turns can be used instead of the 100-turn test, for accuracy and measurement ease of the 1550 nm bend sensitivity. In this case, the loop diameter, number of turns, and the maximum permissible bend loss for the several-turn test, should be chosen, so as to correlate with the 1.0 dB loss recommendation of the 37.5 mm radius 100-turn functional test.

1.7 *Material properties of the fibre*

1.7.1 *Fibre materials*

The substances of which the fibres are made should be indicated.

Note — Care may be needed in fusion splicing fibres of different substances. Provisional results indicate that adequate splice loss and strength can be achieved when splicing different high-silica fibres.

1.7.2 *Protective materials*

The physical and chemical properties of the material used for the fibre primary coating, and the best way of removing it (if necessary) should be indicated. In the case of a single jacketed fibre similar indications shall be given.

1.8 *Refractive index profile*

The refractive index profile of the fibre does not generally need to be known; if one wishes to measure it, the reference test method in Recommendation G.651 may be used.

1.9 *Examples of fibre design guidelines*

Supplement No. 33 gives an example of fibre design guidelines for matched-cladding fibres used by two organizations.

2 **Factory length specifications**

Since the geometrical and optical characteristics of fibres given in § 1 are barely affected by the cabling process, § 2 will give recommendations mainly relevant to transmission characteristics of cabled factory lengths.

Environmental and test conditions are paramount and are described in the guidelines for test methods.

2.1 *Attenuation coefficient*

Optical fibre cables covered by this Recommendation generally have attenuation coefficients in the below 1.0 dB/km in the 1300 nm wavelength region, and below 0.5 dB/km in the 1550 nm wavelength region.

Note — The lowest values depend on the fabrication process, fibre composition and design, and cable design. Values in the range 0.3-0.4 dB/km in the 1300 nm region and 0.15-0.25 dB/km in the 1550 nm region have been achieved.

2.2 *Chromatic dispersion coefficient*

The maximum chromatic dispersion coefficient shall be specified by:

— the allowed range of the zero-dispersion wavelength between λ_{omin} = 1295 nm and λ_{omax} = 1322 nm;

— the maximum value S_{omax} = 0.095 ps/(nm^2 | (mu | m) of the zero-dispersion slope.

The chromatic dispersion coefficient limits for any wavelength λ within the range 1270-1340 nm shall be calculated as

$D_1(\lambda)$ =
[Formula Deleted]
[λ— (*l $$Ei :4;omin _ / (*l 3]

$D_2(\lambda)$ =
fIS~ omax~
[λ— (*l $$Ei :4;omax _ / (*l 3]

Note 1 — The values of λ_{omin}, λ_{omax}, and S_{omax} yield chromatic dispersion coefficient magnitudes | | fID$_1$ | and | | fID$_2$ | equal to or smaller than the maximum chromatic dispersion coefficients in the table:

H.T. [T1.652]

Wavelength (nm)	{ Maximum chromatic dispersion coefficient [ps/(nm×km)] }
1285 | (hy | 330	3.5
1270 | (hy | 340	6 |
1550	20 |

Table [T1.652], p.

(An exception occurs at 1285 nm, where the value of | | fID$_2$ | is 3.67 ps/(nm | (mu | m). A smaller value would be achieved by reducing S_{omax} or λ_{omax} ; this item requires further study.)

Note 2 — Use of these equations in the 1550 nm region should be approached with caution.

Note 3 — For high capacity (for example, 4 × 140 Mb/s or above) or long length systems, a narrower range of λ_{omin}, λ_{omax} may need to be specified, or if possible, a smaller value of S_{omax} be chosen.

Note 4 — It is not necessary to measure chromatic dispersion coefficient of single mode fibre on a routine basis.

3 Elementary cable sections

An elementary cable section usually includes a number of spliced factory lengths. The requirements for factory lengths are given in § 2 of this Recommendation. The transmission parameters for elementary cable sections must take into account not only the performance of the individual cable lengths but also amongst other factors, such things as splice losses and connector losses (if applicable).

3.1 *Attenuation*

The attenuation A of an elementary cable section is given by:

$$A = \sum_{n=1}^{m} \alpha_n L_n + a_s x + a_c y$$

where

α_n	=	attenuation coefficient of n th fibre in elementary cable section,
L_n	=	length of n th fibre,
m	=	total number of concatenated fibres in elementary cable section,
a_s	=	mean splice loss,
x	=	number of splices in elementary cable section,
a_c	=	mean loss of line connectors,
y	=	number of line connectors in elementary cable section (if provided).

A suitable allowance should be allocated for a suitable cable margin for future modifications of cable configurations (additional splices, extra cable lengths, ageing effects, temperature variations, etc.).

The above expression does not include the loss of equipment connectors.

The mean loss is used for the loss of splices and connectors. The attenuation budget used in designing an actual system should account for the statistical variations in these parameters.

3.2 *Chromatic dispersion*

The chromatic dispersion in ps can be calculated from the chromatic dispersion coefficients of the factory lengths, assuming a linear dependence on length, and with due regard for the signs of the coefficients and system source characteristics (see § 2.2).

ANNEX A

(to Recommendation G.652)

Meaning of the terms used in the Recommendation

The terms listed in this Annex are specific for single-mode fibres. Other terms used in this Recommendation have the same meaning as given in Annex A to Recommendation G.651.

A.1 **mode field diameter**

The mode field diameter $2w$ is found by applying one of the following definitions. The integration limits are shown to be 0 to ∞, but it is understood that this notation implies that the integrals be truncated in the limit of increasing argument. While the maximum physical value of the argument q is [Formula Deleted] the integrands rapidly approach zero before this value is reached.

i) FAR-FIELD DOMAIN: In this domain theree different measurement implementations are possible:

a) FAR-FIELD SCAN: The far-field intensity distribution $F^2(q)$ is measured as a function of the far-field angle θ, and the mode field diameter (MDF) at the wavelength λ is

2*w* =

[Formula Deleted]

[2$$ 4o (if ∫ 0 fIq 3 f IF 2(q) dq $$ 4u (if ∫ 0 f IqF 2(q) dq $$ 4e]

—1/2,

where *q* =

[Formula Deleted]

(1)

b) KNIFE-EDGE SCAN: The knife-edge power transmission function *K* (*x*) is measured as a function of knife-edge lateral offset *x* with the plane of the knife-edge separated by a distance *D* from the fibre, and the MFD is

2*w* =

[Formula Deleted]

[4$$ 4o (if ∫ 0 fIK ‘ (x) q 2 f Idq $$ 4u (if ∫ 0 f IK ‘ (x) dq $$ 4e]

—1/2,

where *x* =

D tan θ, *K* ‘

(*x*) =

f IdK (*x*) / *fIdx* and *q* =

[Formula Deleted]

(2)

c) VARIABLE APERTURE TECHNIQUE: The complementary aperture power transmission function α(*x*) is measured as a function of aperture radius *x* with the plane of the aperture separated by a distance *D* from the fibre, and the MFD is

2*w* =

[Formula Deleted]

[4 (if ∫ 0 fIa (x) qdq]

—1/2, where *x* =

D tan θ and *q* =

[Formula Deleted]

(3)

ii) OFFSET JOINT DOMAIN: The power transmission coefficient *T* (δ) is measured as a function of the transverse offset δ and

2*w* = 2

[—2 $$ 1o T(0)$$ 3u [f Id 2 f IT / f Id δ2] (*d =0 $$ 3e]

1/2

(4)

iii) NEAR-FIELD DOMAIN: The near field intensity distribution $f^2(r)$ is measured as a function of the radial coordinate *r* and

2*w* = 2

[2$$ 4o (if ∫ 0 fIrf 2(r) dr $$ 4u (if ∫ 0 f Ir [f Idf (r) / f Idr] $$2x 2 dr $$ 4e]

1/2

(5)

Note — The mathematical equivalence of these definitions results from transform relations between measurement results obtained by different implementation. These are summarized in Figure A-1/G.652.

Figure A-1/G.652, p.

A.2 **cladding surface**

The outer surface of the glass that comprises the optical fibre.

A.3 **cladding surface centre**

For a cross-section of an optical fibre, it is the position of the centre of the circle which best fits the locus of the cladding surface in the given cross-section.

Note — The best fit method has to be specified, and is currently under study.

A.4 **cladding surface diameter**

The diameter of the circle defining the cladding centre.

Note — For a nominally circular fibre, the cladding surface diameter in any orientation of the cross-section is the largest distance across the cladding.

A.5 **non-circularity of the cladding surface**

The difference between the maximum cladding surface diameter D_{max} and minimum cladding surface diameter D_{min} (with respect to the common cladding surface centre) divided by the nominal cladding diameter, D, i.e.,

$$Non\text{-}circularity = (D_{max}$$

— D

D_{min}

Note — The maximum and minimum cladding surface diameters are respectively the largest and smallest distances between the two intersections of a line through the cladding centre with the cladding surface.

A.6 **mode field**

The mode field is the single-mode field distribution giving rise to a spatial intensity distribution in the fibre.

A.7 **mode field centre**

The mode field centre is the position of the centroid of the spatial intensity distribution in the fibre.

Note 1 — The centroid is located at r_c, and is the normalized intensity-weighted integral of the position vector $\vec{r}$.

$$\vec{r}_c = \frac{\iint_{AREA} \vec{r}\, I(\vec{r})\, dA}{\iint_{AREA} I(\vec{r})\, dA}$$

Note 2 — For fibres considered in this Recommendation, the correspondence between the position of the centroid as defined and the position of the maximum of the spatial intensity distribution requires further study.

A.8 **mode field concentricity error**

The distance between the mode field centre and the cladding surface centre.

A.9 **mode field non-circularity**

Since it is not normally necessary to measure mode field non-circularity for acceptance purposes (as stated in § 1.4.1) a definition of mode field non-circularity is not necessary in this context.

A.10 **cut-off wavelength**

The cut-off wavelength is the wavelength greater than which the ratio between the total power, including launched higher order modes, and the fundamental mode power has decreased to less than a specified value, the modes being substantially uniformly excited.

Note 1 — By definition, the specified value is chosen as 0.1 dB for a substantially straight 2 metre length of fibre including one single loop of radius 140 mm.

Note 2 — The cut-off wavelength defined in this Recommendation is generally different from the theore tical cut-off wavelength that can be computed from the refractive index profile of the fibre. The theoretical cut-off wavelength is a less useful parameter for determining fibre performance in the telecommunication network.

Note 3 — In § 1.5, two types of cut-off wavelength are described:

i) a cut-off wavelength λ_c | measured in a short length of uncabled primary-coated fibre;

ii) a cut-off wavelength $\lambda_{c\backslash \mathrm{d}c}$ | measured in a cabled fibre in a deployment condition.

To avoid modal noise and dispersion penalties, the cut-off wavelength $\lambda_{c\backslash \mathrm{d}c}$ | of the shortest cable length (including repair lengths when present) should be less than the lowest anticipated system wavelength, λ_s:

$$\lambda_{c\backslash \mathrm{d}c} < \lambda_s \tag{1}$$

This ensures that each individual cable section is sufficiently single mode. Any joint that is not perfect will create some higher order ($LP_{1\backslash \mathrm{d}1}$) mode power and single mode fibres typically support this mode for a short distance (of the order of metres, depending on the deployment conditions). A minimum distance must therefore be specified between joints, in order to give the fibre sufficient distance to attenuate the $LP_{1\backslash \mathrm{d}1}$ mode before it reaches the next joint. If inequality (1) is satisfied in the shortest cable section, it will be satisfied *a fortiori* in all longer cable sections, and single mode system operation will occur regardless of the elementary cable section length.

Specifying $\lambda_{c\backslash dc} < \lambda_s$ for the shortest cable length (including loops in the splice enclosure) ensures single mode operation. It is frequently more convenient, however, to measure λ_c, which requires only a two-metre length of uncabled fibre. λ_c depends on the fibre type, length, and bend radius, and $\lambda_{c\backslash dc}$, in addition, depends on the structure of a particular cable. The relationship between λ_c and $\lambda_{c\backslash dc}$, therefore, is dependent on both the fibre and cable designs. In general, λ_c is several tens of nm larger than $\lambda_{c\backslash dc}$; λ_c can even be larger than the system wavelength, without violating inequality (1). Higher values of λ_c produce tighter confinement of the $LP_{0\backslash d1}$ mode and, therefore, help to reduce potential bending losses in the 1550 nm wavelength region.

Short fibre lenghts (<20m) are frequently attached to sources and detectors, and are also used as jumpers for interconnections. The cut-off wavelength of these fibres, as deployed, should also be less than λ_s. Among the means of avoiding modal noise in this case are:

a) selecting only fibres with sufficiently low λ_c for such uses;

b) deployment of such fibres with small radius bends.

A.11 **chromatic dispersion**

The spreading of a light pulse per unit source spectrum width in an optical fibre caused by the different group velocities of the different wavelengths composing the source spectrum.

Note — The chromatic dispersion may be due to the following contributions: material dispersion, waveguide dispersion, profile dispersion. Polarization dispersion does not give appreciable effects in circularly-symmetric fibres.

A.12 **chromatic dispersion coefficient**

The chromatic dispersion per unit source spectrum width and unit length of fibre. It is usually expressed in ps/(nm $\times$ km).

A.13 **zero-dispersion slope**

The slope of the chromatic dispersion coefficient versus wavelength curve at the zero-dispersion wavelength.

A.14 **zero-dispersion wavelength**

That wavelength at which the chromatic dispersion vanishes.

ANNEX B

(to Recommendation G.652)

Test methods for single-mode fibres

Both reference and alternative test methods are usually given in this Annex for each parameter and it is the intention that both the RTM and the ATM(s) may be suitable for normal product acceptance purposes. However, when using an ATM, should any discrepancy arise it is recommended that the RTM be employed as the technique for providing the definitive measurement results.

B.1 — Section I — *Test methods for the mode field diameter of single-mode fibres*

B.1.1 *Reference test method for the mode field diameter of single-mode fibres*

B.1.1 *Objective*

The mode field diameter may be determined in the far-field domain from the far field intensity distribution, $F^2(q)$, from the knife-edge transmission function, $K(x)$, or from the complementary aperture power transmission function, $\alpha(x)$; in the offset join domain from the square of the autocorrelation function, $T(\delta)$; in the near-field domain from the near-field intensity distribution, $f^2(r)$; according to the equivalent definitions shown in § A.1 in Annex A to Recommendation G.652.

B.1.1.2 *Test apparatus*

B.1.1.2.1 *General*

For-near field measurements, the magnifying optics are required to create an image of the output end of the fibre in the plane of the detector. For offset joint measurements a means of traversing one fibre end face across another is required. For the three far-field measurements, appropriate scanning devices are required.

B.1.1.2.2 *Light source*

The light source shall be stable in position, intensity and wavelength over a time period sufficiently long to complete the measurement procedure. The spectral characteristics of the source should be chosen to preclude multimode operation.

B.1.1.2.3 *Modulation*

It is customary to modulate the light source in order to improve the signal/noise ratio at the receiver. If such a procedure is adopted, the detector should be linked to a signal processing system synchronous to the source modulation frequency. The detecting system should have substantially linear sensitivity characteristics.

B.1.1.2.4 *Launching conditions*

The launching conditions used must be sufficient to excite the fundamental ($LP_{0\backslash d1}$) mode. For example, suitable launching techniques could be:

a) jointing with a fibre,

b) launching with a suitable system of optics.

Care should be taken that higher order modes do not propagate. For this purpose it may be necessary to introduce a loop of suitable radius or another mode filter in order to remove higher order modes.

B.1.1.2.5 *Cladding mode strippers*

Precautions shall be taken to prevent the propagation and detection of cladding modes.

B.1.1.2.6 *Specimen*

The specimen shall be a short length of the optical fibre to be measured. Primary fibre coating shall be removed from the section of the fibre inserted in the mode stripper, if used. The fibre ends shall be clean, smooth and perpendicular to fibre axes. It is recommended that the end faces be flat and perpendicular to the fibre axes to within 1°. For the offset joint technique, the fibre will be cut into two approximately equal lengths.

B.1.1.2.7 *Offset or scan apparatus*

Due to the characteristically narrower near-field intensity distributions and wider far-field intensity distributions of G.653 fibres compared with G.652 fibres, additional precautions must be taken as detailed below.

One of the following shall be used:

I *Far-field domain*

a) *Far field scan system*

A mechanism to scan the far-field intensity distribution shall be used (for example, a scanning photodetector with pinhole aperture or a scanning pig-tailed photodetector). The scan may be either angular or linear. The detector should be at least 20 mm from the fibre end, and the detector's active area should not subtend too large an angle in the far field. This can be assured by placing the detector at a distance from the fibre end greater than $20wb/\lambda$, where $2w$ is the expected mode field diameter of the fibre to be measured, and b is the diameter of the active area of the detector. The scan half-angle should be 25° or greater. Alternatively, the scan should extend to at least —50 dB of the zero-angle intensity.

b) *Knife-edge assembly*

A mechanism to scan a knife-edge linearly in a direction orthogonal to the fibre axis and to the edge of the blade is required. Light transmitted by the knife-edge is collected and focused onto the detector. The collection optics should have a NA of 0.4 or greater.

c) *Aperture assembly*

A mechanism containing at least twelve apertures spanning the half-angle range of numerical apertures from 0.02 to 0.4 should be used. Light transmitted by the aperture is collected and focused onto the detector.

II *Offset joint domain*

Traversing joint

The joint shall be constructed such that the relative offset of the fibre axes can be adjusted. A means of measuring the offset to within 0.1 µm is recommended. The optical power transmitted through the traversing joint is measured by a detector. Particular care should be taken with regard to the precision and accuracy of the offset apparatus.

III *Near-field domain*

Near-field imaging optics

Magnifying optics (e.g., a microscope objective) shall be employed to enlarge and focus an image of the fibre near field onto the plane of a scanning detector (for example, a scanning photodetector with a pinhole aperture or a scanning pig-tailed photodetector). The numerical aperture and magnification shall be selected to be compatible with the desired spatial resolution. For calibration, the magnification of the optics should have been measured by scanning the length of a specimen whose dimensions are indepently known with sufficient accuracy.

Note — The NA of the collecting optics in I b) and I c) must be large enough not to affect the measurement results.

B.1.1.2.8 *Detector*

A suitable detector shall be used. The detector must have linear characteristics.

B.1.1.2.9 *Amplifier*

An amplifier should be employed in order to increase the signal level.

B.1.1.2.10 *Data acquisition*

The measured signal level shall be recorded and processed according to the technique used.

B.1.1.2.11 *Measurement procedure*

The launch end of the fibre shall be aligned with the launch beam, and the output end of the fibre shall be aligned to the appropriate output device.

One of the following procedures should be followed.

I *Far-field domain*

a) By scanning the detector in fixed steps, the far-field intensity distribution $F^2(q)$ is measured, and the mode field diameter is calculated from § A.1, Equation (1) in Annex A.

b) The power transmitted by the knife-edge is measured as a function of knife-edge position. This function, $K(x)$, is differentiated and the mode field diameter is found from § A.1, Equation (2) in Annex A.

c) The power transmitted by each aperture, $P(x)$, is measured, and the complementary aperture transmission function, $a(x)$, is found as:

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

where P_{max} is the power transmitted by the largest aperture and x is the aperture radius. The mode field diameter is computed from § A.1, Equation (3) in Annex A.

II *Offset joint domain*

By offsetting the joint transversely in discrete steps, the power transmission coefficient $T(\delta)$, is measured, and the mode field diameter is calculated from § A.1, Equation (4) in Annex A.

III *Near-field domain*

The near field of the fibre is enlarged by the magnifying optics and focused onto the plane of the detector. The focusing shall be performed with maximum accuracy, in order to reduce dimensional errors due to the scanning of a defocused image. The near field intensity distribution, $f^2(r)$, is scanned and the mode field diameter is calculated from § A.1, Equation (5) in Annex A. Alternatively, the near field intensity distribution $f^2(r)$ may be transformed into the far field domain using a Hankel transform and the resulting transformed far field $F^2(q)$ may be used to compute the mode field diameter from § A.1, Equation (1) in Annex A.

B.1.1.2.12 *Presentation of the results*

The following details shall be presented:

a) Measurement technique used, including test set-up arrangement, dynamic range of the measurement system, processing algorithms, and a description of the imaging, offsetting, or scanning devices used.

b) If the offset joint technique is used, the employed fitting method should be indicated (including the scan angle or NA, if applicable).

c) Launching conditions.

d) Wavelength and spectral linewidth FWHM of the source.

e) Fibre identification and length.

f) Type of cladding mode stripper and filter (if applicable).

g) Magnification of the apparatus (if applicable).

h) Type and dimensions of the detector.

i) Temperature of the sample and environmental conditions (when necessary).

j) Indication of the accuracy and repeatability.

k) Mode field diameter.

Note — As with other test methods, the apparatus and procedure given above cover only the essential basic features of the reference test method. It is assumed that the detailed instrumentation will incorporate all necessary measures to ensure stability, noise elimination, signal-to-noise ratio, etc.

B.2 — Section II — *Test methods for the geometrical characteristics excluding the mode field diameter*

B.2.1 *Reference test method: The transmitted near-field technique*

B.2.1.1 *General*

The transmitted near-field technique shall be used for the measurement of the geometrical characteristics of single-mode optical fibres. Such measurements are performed in a manner consistent with the relevant definitions.

The measurement is based on the scanning of the magnified image(s) of the output end of the fibre under test over the cross-section(s) where the detector is placed.

B.2.1.2 *Test apparatus*

A schematic diagram of the test apparatus is shown in Figure B-1/G.652.

B.2.1.2.1 *Light source*

A nominal 1550 nm light source for illuminating the core shall be used. The light source shall be adjustable in intensity and stable in position, intensity and wavelength over a time period sufficiently long to complete the measurement procedure. The spectral characteristics of this source should be chosen to preclude multimode operation. A second light source with similar characteristics can be used, if necessary, for illuminating the cladding. The spectral characteristics of the second light source must not cause defocussing of the image.

B.2.1.2.2 *Launching conditions*

The launch optics, which will be arranged to overfill the fibre, will bring a beam of light to a focus on the flat input end of the fibre.

B.2.1.2.3 *Mode filter*

In the measurement, it is necessary to assure single-mode operation at the measurement wavelength. In these cases, it may be necessary to introduce a bend in order to remove the LP_{11} mode.

B.2.1.2.4 *Cladding mode stripper*

A suitable cladding mode stripper shall be used to remove the optical power propagating in the cladding. When measuring the geometrical characteristics of the cladding only, the cladding mode stripper shall not be present.

B.2.1.2.5 *Specimen*

The specimen shall be a short length of the optical fibre to be measured. The fibre ends shall be clean, smooth and perpendicular to fibre axis.

B.2.1.2.6 *Magnifying optics*

The magnifying optics shall consist of an optical system (e.g., a microscope objective) which magnifies the specimen output near-field, focussing it onto the plane of the scanning detector. The numerical aperture and hence the resolving power of the optics shall be compatible with the measuring accuracy required, and not lower than 0.3. The magnification shall be selected to be compatible with the desired spatial resolution, and shall be recorded.

Image shearing techniques could be used in the magnifying optics to facilitate accurate measurements.

Note — The validity of the image shearing technique is under study, and needs to be confirmed.

B.2.1.2.7 *Detector*

A suitable detector shall be employed which provides the point-to-point intensity of the transmitted near-field pattern(s). For example, any of the following techniques can be used:

a) scanning photodetector with pinhole aperture;

b) scanning mirror with fixed pinhole aperture and photodetector;

c) scanning vidicon, charge coupled devices or other pattern/intensity recognition devices.

The detector shall be linear (or shall be linearized) in behaviour over the range intensities encountered.

B.2.1.2.8 *Amplifier*

An amplifier may be employed in order to increase the signal level. The bandwidth of the amplifier shall be chosen according to the type of scanning used. When scanning the output end of the fibre with mechanical or optical systems, it is customary to modulate the optical source. If such a procedure is adopted, the amplifier should be linked to the source modulation frequency.

B.2.1.2.9 *Data acquisition*

The measured intensity distribution can be recorded, processed and presented in a suitable form, according to the scanning technique and to the specification requirements.

B.2.1.3 *Procedure*

B.2.1.3.1 *Equipment calibration*

For the equipment calibration the magnification of the magnifying optics shall be measured by scanning the image of a specimen whose dimensions are already known with suitable accuracy. This magnification shall be recorded.

B.2.1.3.2 *Measurement*

The launch end of the fibre shall be aligned with the launch beam, and the output end of the fibre shall be aligned to the optical axis of the magnifying optics. For transmitted near field measurement, the focussed image(s) of the output end of the fibre shall be scanned by the detector, according to the specification requirements. The focussing shall be performed with maximum accuracy, in order to reduce dimensional errors due to the scanning of a defocussed image. The desired geometrical parameters are then calculated according to the definitions.

B.2.1.4 *Presentation of the results*

The following details shall be presented:

a) test set-up arrangement, with indication of the scanning technique used;

b) launching conditions;

c) spectral characteristics of the source(s);

d) fibre identification and length;

e) type of mode filter (if applicable);

f) magnification of the magnifying optics;

g) type and dimensions of the scanning detector;

h) temperature of the sample and environmental conditions (when necessary);

i) indication of the accuracy and repeatability;

j) resulting dimensional parameters, such as cladding diameters, cladding non-circularities, mode field concentricity error, etc.

FIGURE B-1/G.652, p.

B.2.2 *Alternative test method: the refracted near-field technique*

This technique is described in Recommendation G.651. The decision levels on the various refractive index difference interfaces are defined as:

Core/cladding 50%

Cladding/index matching fluid 50%

Geometry analyses consistent with the terms in Annex A, G.652, can be achieved by raster scanning of the input light spot.

B.2.3 *Alternative test method: the side-view method*

The validity of the side-view method for Recommendation G.653 fibres needs to be confirmed.

B.2.3.1 *Objective*

The side-view method is applied to single-mode fibres to determine geometrical parameters (mode field concentricity error (MFCE)), cladding diameter and cladding non-circularity) by measuring the intensity distribution of light that is refracted inside the fibre.

B.2.3.2 *Test apparatus*

A schematic diagram of the test apparatus is shown in Figure B-2/G.652.

B.2.3.2.1 *Light source*

The emitted light shall be collimated, adjustable in intensity and stable in position, intensity and wavelength over a time period sufficiently long to complete the measuring procedure. A stable and high intensity light source such as a light emitting diode (LED) may be used.

B.2.3.2.2 *Specimen*

The specimen to be measured shall be a short length of single-mode fibre. The primary fibre coating shall be removed from the observed section of the fibre. The surface of the fibre shall be kept clean during the measurement.

B.2.3.2.3 *Magnifying optics*

The magnifying optics shall consist of an optical system (e.g., a microscope objective) which magnifies the intensity distribution of refracted light inside the fibre onto the plane of the scanning detector. The observation plane shall be set at a fixed distance forward from the fibre axis. The magnification shall be selected to be compatible with the desired spatial resolution and shall be recorded.

B.2.3.2.4 *Detector*

A suitable detector shall be employed to determine the magnified intensity distribution in the observation plane along the line perpendicular to the fibre axis. A vidicon or charge coupled device can be used. The detector must have linear characteristics in the required measuring range. The detector's resolution shall be compatible with the desired spatial resolution.

B.2.3.2.5 *Data processing*

A computer with appropriate software shall be used for the analysis of the intensity distributions.

B.2.3.3 *Procedure*

B.2.3.3.1 *Equipment calibration*

For equipment calibration the magnification of the magnifying optics shall be measured by scanning the length of a specimen whose dimensions are already known with suitable accuracy. This magnification shall be recorded.

B.2.3.3.2 *Measurement*

The test fibre is fixed in the sample holder and set in the measuring system. The fibre is adjusted so that its axis is perpendicular to the optical axis of the measuring system.

Intensity distributions in the observation plane along the line perpendicular to the fibre axis (a — a' in A, in Figure B-2/G.652) are recorded (shown as B) for different viewing directions, by rotating the fibre around its axis, keeping the distance between the fibre axis and the observation plane constant. Cladding diameter and the central position of the fibre are determined by analyzing the symmetry of the diffraction pattern (shown as b). The central position of the core is determined by analyzing the intensity distribution of converged light (shown as c). The distance between the central position of the fibre and that of the core corresponds to the nominal observed value of MFCE.

As shown in Figure B-3/G.652, fitting the sinusoidal function to the experimentally obtained values of the MFCE plotted as a function of the rotation angle, the actual MFCE is calculated as the product of the maximum amplitude of the sinusoidal function and magnification factor with respect to the lens effect due to the cylindrical structure of the fibre. The cladding diameter is evaluated as an averaged value of measured fibre diameters at each

rotation angle, resulting in values for maximum and minimum diameters to determine the value of cladding non-circularity according to the definition.

Figure B-2/G.652, p.4

Figure B-3/G.652, p.5

B.2.3.3.3 *Presentation of the results*

The following details shall be presented:

a) test arrangement;

b) fibre identification;

c) spectral characteristics of the source;

d) indication of repeatability and accuracy;

e) plot of nominal MFCE versus rotation angle;

f) MFCE, cladding diameter and cladding non-circularity;

g) temperature of the sample and environmental conditions (if necessary).

B.2.4 *Alternative test method: the transmitted near-field image technique*

B.2.4.1 *General*

The transmitted near-field image technique shall be used for the measurement of the geometrical characteristics of single-mode optical fibres. Such measurements are performed in a manner compatible with the relevant definitions.

The measurement is based on analysis of the magnified image(s) of the output end of the fibre under test.

B.2.4.2 *Test apparatus*

A schematic diagram of the test apparatus is shown in Figure B-4/G.652.

B.2.4.2.1 *Light source*

The light source for illuminating the core shall be adjustable in intensity and stable in position and intensity over a time period sufficiently long to complete the measurement procedure. A second light source with similar characteristics can be used, if necessary, for illuminating the cladding. The spectral characteristics of the second light source must not cause defocussing of the image.

B.2.4.2.2 *Launching conditions*

The launch optics, which will be arranged to overfill the fibre, will bring the beam of light to a focus on the flat input end of the fibre.

B.2.4.2.3 *Cladding mode stripper*

A suitable cladding mode stripper shall be used to remove the optical power propagating in the cladding. When measuring the geometrical characteristics of the cladding only, the cladding mode stripper shall not be present.

B.2.4.2.4 *Specimen*

The specimen shall be a short length of the optical fibre to be measured. The fibre ends shall be clean, smooth and perpendicular to the fibre axis.

B.2.4.2.5 *Magnifying optics*

The magnifying optics shall consist of an optical system (e.g., a microscope objective) which magnifies the specimen output near field. The numerical aperture and hence the resolving power of the optics shall be compatible with the measuring accuracy required, and not lower than 0.3. The magnification shall be selected to be compatible with the desired spatial resolution, and shall be recorded.

Image shearing techniques could be used in the magnifying optics to facilitate accurate measurements.

B.2.4.2.6 *Detection*

The fibre image shall be examined and/or analyzed. For example, either of following techniques can be used:

a) image shearing ;

b) grey-scale analysis of an electronically recorded image.

B.2.4.2.7 *Data acquisition*

The data can be recorded, processeed and presented in a suitable form, according to the technique and to the specification requirements.

B.2.4.3 *Procedure*

B.2.4.3.1 *Equipment calibration*

For the equipment calibration the magnification of the magnifying optics shall be measured by scanning the image of a specimen whose dimensions are already known with suitable accuracy. This magnification shall be recorded.

B.2.4.3.2 *Measurement*

The launch end of the fibre shall be aligned with the launch beam, and the output end of the fibre shall be aligned to the optical axis of the magnifying optics. For transmitted near-field measurement, the focussed image(s) of the ouput end of the fibre shall be examined according to the specification requirements. Defocussing errors should be minimized to reduce dimensional errors in the measurement. The desired geometrical parameters are then calculated.

B.2.4.4 *Presentation of the results*

a) test set-up arrangement, with indication of the technique used;

b) launching conditions;

c) spectral characteristics of the source;

d) fibre identification and length;

e) magnification of the magnifying optics;

f) temperature of the sample and environmental conditions (when necessary);

g) indication of the accuracy and repeatability;

h) resulting dimensional parameters, such as cladding diameters, cladding non-circularities, mode field concentricity error, etc.

The validity of the image shearing technique is under study and needs to be confirmed.

Figure B-4/G.652, p.

B.3 — Section III — *Test methods for the cut-off wavelength*

B.3.1 *Reference test method for the cut-off wavelength (λ_c) of the primary coated fibre: the transmitted power technique*

B.3.1.1 *Objective*

This cut-off wavelength measurement of single-mode fibres is intended to assure effective single-mode operation above a specified wavelength.

B.3.1.2 *The transmitted power technique*

This method uses the variation with wavelength of the transmitted power of a short length of the fibre under test, under defined conditions, compared to a reference transmitted power. There are two possible ways to obtain this reference power:

a) the test fibre with a loop of smaller radius, or

b) a short (1-2 m) length of multimode fibre.

B.3.1.2.1 *Test apparatus*

B.3.1.2.1.1 *Light source*

A light source with linewidth not exceeding 10 nm (FWHM), stable in position, intensity and wavelength over a time period sufficient to complete the measurement procedure, and capable of operating over a sufficient wavelength range, shall be used.

B.3.1.2.1.2 *Modulation*

It is customary to modulate the light source in order to improve the signal/noise ratio at the receiver. If such a procedure is adopted, the detector should be linked to a signal processing system synchronous to the source modulation frequency. The detecting system should be substantially linear.

B.3.1.2.1.3 *Launching conditions*

The launching conditions must be used in such a way to excite substantially uniformly both $LP_{0\backslash d1}$and $LP_{1\backslash d1}$modes. For example, suitable launching techniques could be:

a) jointing with a multimode fibre, or

b) launching with a suitable large spot — large NA optics.

B.3.1.2.1.4 *Cladding mode stripper*

The cladding mode stripper is a device that encourages the conversion of cladding modes to radiation modes; as a result, cladding modes are stripped from the fibre. Care should be taken to avoid affecting the propagation of the $LP_{1\backslash d1}$ mode.

B.3.1.2.1.5 *Optical detector*

A suitable detector shall be used so that all of the radiation emerging from the fibre is intercepted. The spectral response should be compatible with the spectral characteristics of the source. The detector must be uniform and have linear sensitivity.

B.3.1.2.2 *Procedure*

B.3.1.2.2.1 *Standard test sample*

The measurement shall be performed on a 2 m length of fibre. The fibre is inserted into the test apparatus and bent to form a loosely constrained loop. The loop shall complete one full turn of a circle of 140 mm radius. The remaining part of the fibre shall be substantially free of external stresses. While some incidental bends of larger radii are permissible, they must not introduce a significant change in the measurement result. The ouput power P_1 (λ) shall be recorded versus λ in a sufficiently wide range around the expected cut-off wavelength.

Note — The presence of a primary coating on the fibre usually does not affect the cut-off wavelength. However, the presence of a secondary coating may result in a cut-off wavelength that may be significantly shorter than that of the primary coated fibre.

B.3.1.2.2.2 *Transmission through the reference sample*

Either method a) or b) may be used.

a) Using the test sample, and keeping the launch conditions fixed, an output power $P_2(\lambda)$ is measured over the same wavelength range with at least one loop of sufficiently small radius in the test sample to filter the $LP_{1\d1}$ mode. A typical value for the radius of this loop is 30 mm.

b) With a short (1-2 m) length of multimode fibre, an output power P_3 (λ) over the same wavelength range.

Note — The presence of leaky modes may cause ripple in the transmission spectrum of the multimode reference fibre, affecting the result. To reduce this problem, light-launching conditions may be restricted to fill only 70% of the multimode fibre's core diameter and NA or a suitable mode filter may be used.

B.3.1.2.2.3 *Calculations*

The logarithmic ratio between transmitted powers $P_1(\lambda)$ and P_i (λ) is calculated as:

$$R(\lambda) = 10 \log [P_1(\lambda)/P_i(\lambda)]$$

where

i = 2 or 3, methods a) or b) respectively.

Note — In method a) the small mode filter fibre loop eliminates all modes except the fundamental for wavelengths greater than a few tens of nm below the cut-off wavelength λ_c. For wavelengths more than several hundred nm above λ_c, even the fundamental mode may be strongly attenuated by the loop. R (λ) is equal to the logarithmic ratio between the total power emerging from the sample, including the $LP_{1\d1}$ mode power, and the fundamental mode power. When the modes are uniformly excited in accordance with B.1.2.1.3, R (λ) then also yields the $LP_{1\d1}$ mode attenuation A (λ) in dB in the test sample:

$$A(\lambda) = 10 \log [(P_1(\lambda)/P_2(\lambda) - 1)/2]$$

B.3.1.2.2.4 *Determination of cut-off wavelength*

If method a) is used, λ_c | is determined as the largest wavelength at which R (λ) is equal to 0.1 dB (see Figure B-5/G.652).

If method b) is used, λ_c is determined by the intersection of a plot of R (λ) and a straight line (2) displaced 0.1 dB and parallel to the straight line (1) fitted to the long wavelength portion of R (λ) (see Figure B-6/G.652).

Note — According to the definition, the $LP_{1\d1}$ mode attenuation in the test sample is 19.3 dB at the cut-off wavelength.

B.3.2.1.2.2.5 *Presentation of results*

a) test set-up arrangement;

b) launching condition;

c) type of reference sample;

d) temperature of the sample and environmental conditions (if necessary);

e) fibre identification;

f) wavelength range of measurement;

g) cut-off wavelength;

h) plot of R (λ) (if required).

B.3.2 *Alternative test method for* λ *split-mandrel technique*

B.3.2.1 *Objective* through B.3.2.2.1.5 *Optical detector* (as in B.3.1.1 through B.3.1.2.1.5)

B.3.2.2.2 *Procedure*

B.3.2.2.2.1 *Standard test sample*

Figure B-5/G.652, p.

Figure B-6/G.652, p.

The measurement shall be performed on a 2 m length of fibre. The fibre is inserted into the test apparatus and bent to form a loosely constrained loop. The loop shall contain a full turn (360 degrees) consisting of two arcs (180 degrees each) of 140 mm radius connected by tangents. The remaining part of the fibre shall be substantially free of external stresses.

While some incidental bends of larger radii are permissible, they must not introduce a significant change in the measurement result. The output power $P_1(\lambda)$ shall be recorded versus λ in a sufficiently wide range around the expected cut-off wavelength.

As shown in Figure B-7/G.652, the lower semicircular mandrel moves to take any slack from the fibre loop without requiring movement of the launch or receive optics or placing the fibre sample under any significant tension.

B.3.2.2.2.2 through B.3.2.2.2.5 (as in B.3.1.2.2.2 through B.3.1.2.2.5)

Figure B-7/G.652, p.

B.3.3 *Reference test method for the cut-off wavelength (λ_{cc}) of the cable fibre: the transmitted power technique*

B.3.3.1 *Objective*

This cut-off wavelength measurement which is performed on cabled single-mode fibres in a deployment condition which stimulates outside plant minimum cable lengths, is intended to assure effective single-mode operation above a specified wavelength.

B.3.3.2 *The transmitted power technique*

This method uses the variation with wavelength of the transmitted power of the fibre cable under test, under defined conditions, compared to a reference transmitted power. There are two possible ways to obtain this reference power.

a) the cabled test fibre with a loop of smaller radius;

b) a short (1-2 m) length of multimode fibre.

B.3.3.2.1 *Test apparatus*

B.3.3.2.1.1 *Light source* (as in B.3.1.2.1.1)

B.3.3.2.1.2 *Modulation* (as in B.3.1.2.1.2)

B.3.3.2.1.3 *Launching conditions* (as in B.3.1.2.1.3)

B.3.3.2.1.4 *Cladding mode stripper* (as in B.3.1.2.1.4)

B.3.3.2.1.5 *Optical detector* (as in B.3.1.2.1.5)

B.3.3.2.2 *Procedure*

B.3.3.2.2.1 *Standard test sample*

The measurement shall be performed on a length of single-mode fibre in a cable. A cable length of 22 m shall be prepared by exposing 1 m uncabled fibre length at each end, and the resulting 20 m cabled portion shall be laid without any small bends which could affect the measurement value. To simulate the effects of a splice organizer, one loop of XX mm radius shall be applied to each uncabled fibre length (see Figure B-8/G.652). While some incidental bends of larger radii are permissible in the fibre or cable, they must not introduce a significant change in the measurements. The output power $P_1(\lambda)$ shall be recorded versus λ in a sufficiently wide range around the expected cut-off wavelength.

Note — The value of XX is under study. Several Administrations indicated that a value of 45 mm is appropriate. The loops are intended to simulate deployment conditions, and should be chosen according to the practice of a particular Administration. One option to be considered is deleting the loops, if that is the Administration's practice.

B.3.3.2.2.2 *Transmission through the reference sample* (as in B.1.2.2.2)

B.3.3.2.2.3 *Calculations*

The logaritmic ratio between the transmitted powers $P_1(\lambda)$ and $P_1(\lambda)$ is calculated as

$$R(\lambda) = 10 \log [P_1(\lambda)/P_i(\lambda)] \quad \text{(dB)} \tag{1}$$

where i = 2 or 3 for methods a) or b), respectively.

B.3.3.2.2.4 *Determination of cabled fibre cut-off wavelength*

If method a) is used, $\lambda_{c\backslash dc}$ | is determined as the largest wavelength at which $R(\lambda)$ is equal to 0.1 dB (see Figure B-5). If method b) is used, $\lambda_{c\backslash dc}$ is determined by the intersection of a plot of $R(\lambda)$ and a straight line (2) displaced 0.1 dB and parallel to the straight line (1) fitted to the long wavelength portion of $R(\lambda)$ see Figure B-6).

B.3.3.2.2.5 *Presentation of results*

a) test set-up arrangment (including the radius XX of the loops);

b) launching condition;

c) type of reference sample;

d) temperature of the sample and environmental conditions (if necessary);

e) fibre and cable identification;

f) wavelength range of measurement;

g) cabled fibre cut-off wavelength, and plot of $R(\lambda)$ (if required);

h) plot of $R(\lambda)$ (if required).

Figure B-8/G.652, p.

B.4 — Section IV — *Test methods for attenuation measurements*

B.4.1 *Introduction*

B.4.1.1 *Objectives*

The attenuation tests are intended to provide a means whereby a certain attenuation value may be assigned to a fibre length such that individual attenuation values may be added together to determine the total attenuation of a concatenated length.

B.4.1.2 *Definition*

The attenuation $A(\lambda)$ at wavelength λ between two cross-sections and separated by distance L of a fibre is defined, as

$$A(\lambda) = 10 \log [P_1(\lambda)/P_2(\lambda)] \quad \text{(dB)} \tag{1}$$

where $P_1(\lambda)$ is the optical power traversing the cross-section 1 and $P_2(\lambda)$ is the optical power traversing the cross-section 2 at the wavelength λ.

For a uniform fibre, it is possible to define an attenuation per unit length, or an attenuation coefficient which is dependent of the length of the fibre:

$$\alpha(\lambda) = A(\lambda)/L \quad \text{(dB/unit of length)} \tag{2}$$

Note — Attenuation values specified for factory lengths should be measured at room temperature (i.e., a single value in the range 10 to 35 | (deC).

B.4.2 *The reference test method: the cut-back technique*

The cut-back technique is a direct application of the definition in which the power levels P_1 and P_2 are measured at two points of the fibre without change of input conditions. P_2 is the power emerging from the far end of the fibre and P_1 is the power emerging from a point near the input after cutting the fibre.

B.4.2.1 *Test apparatus*

Measurements may be made at one or more spot wavelengths, or alternatively, a spectral response may be required over a range of wavelengths. Diagrams of suitable test equipments are shown as examples in Figure B-9/G.652.

B.4.2.1.1 *Optical source*

A suitable radiation source shall be used, such as a lamp, laser or light emitting diode. The choice of source depends upon the type of measurement. The source must be stable in position, intensity and wavelength over a time period sufficiently long to complete the measurement procedure. The spectral linewidth (FWHM) shall be specified such that the linewidth is narrow compared with any features of the fibre spectral attenuation.

B.4.2.1.2 *Modulation*

It is customary to modulate the light source in order to improve the signal/noise ratio at the receiver. If such a procedure is adopted, the detector should be linked to a signal processing system synchronous to the source modulation frequency. The detecting system should be substantially linear.

B.4.2.1.3 *Launching conditions*

The launching conditions used must be sufficient to excite the fundamental mode. For example, suitable launching techniques could be:

a) jointing with a fibre,

b) launching with a suitable system of optics.

B.4.2.1.4 *Mode filter*

Care must be taken that higher order modes do not propagate through the cut-back length. In these cases, it may be necessary to introduce a bend in order to remove the higher modes.

B.4.2.1.5 *Cladding mode stripper*

A cladding mode stripper encourages the conversion of cladding modes to radiation modes; as a result, cladding modes are stripped from the fibre.

B.4.2.1.6 *Optical detector*

A suitable detector shall be used so that all of the radiation emerging from the fibre is intercepted. The spectral response should be compatible with spectral characteristics of the source. The detector must be uniform and have linear characteristics.

B.4.2.2 *Measurement procedure*

B.4.2.2.1 *Preparation of fibre under test*

Fibre ends shall be substantially clean, smooth, and perpendicular to the fibre axis. Measurements on uncabled fibres shall be carried out with the fibre loose on the drum, i.e., microbending effects shall not be introduced by the drum surface.

B.4.2.2.2 *Procedure*

1) The fibre under test is placed in the measurements set-up. The output power P_2 is recorded.

2) Keeping the launching conditions fixed, the fibre is cut to the cut-back length (for example, 2 m from the launching point). The cladding mode stripper, when needed, is refitted and the output power P_1 from the cut-back length is recorded.

3) The attenuation of the fibre, between the points where P_1 and P_2 have been measured, can be calculated from the definition using P_1 and P_2.

B.4.2.2.3 *Presentation of results*

The following details shall be presented:

a) test set-up arrangement, including source type, source wavelength, and linewidth (FWHM);

b) fibre identification;

c) length of sample;

d) attenuation of the sample quoted in dB;

e) attenuation coefficient quoted in dB/km;

f) indication of accuracy and repeatability;

g) temperature of the sample and environmental conditions (if necessary).

B.4.3 *First alternative test method; the backscattering technique*

Note — This test method describes a procedure to measure the attenuation of a homogenous sample of single-mode optical fibre cable. The technique can be applied to check the optical continuity, physical defects, splices, backscattered light of optical fibre cables and the length of the fibre.

B.4.3.1 *Launching conditions*

The launch beam shall be coaxially incident on the launch end of the fibre; various devices such as index matching materials can be used to reduce Fresnel reflections. The coupling loss shall be minimized.

B.4.3.2 *Apparatus and procedure*

B.4.3.2.1 *General considerations*

The signal level of the backscattered optical signal will normally be small and close to the noise level. In order to improve the signal-to-noise ratio and the dynamic measuring range it is therefore customary to use a high power light source in connection with signal processing of the detected signal. Further, accurate spatial resolution may require adjustment of pulse width in order to obtain a compromise between resolution and pulse energy. Special care should be taken to minimize the Fresnel reflections.

Care must be taken that higher order modes do not propagate.

An example of apparatus is shown in Figure B-10a/G.652.

B.4.3.2.2 *Optical source*

A stable high power optical source of an appropriate wavelength should be used. The wavelength of the source should be registered. The pulse width and repetition rate should be consistent with the desired resolution and the length of the fibre. Optical non-linear effects should not be present in the part of the fibre under test.

B.4.3.2.3 *Coupling device*

The coupling device is needed to couple the source radiation to the fibre and the backscattered radiation to the detector, while avoiding a direct source-detector coupling. Several devices can be used, but devices based on polarization effects should be avoided.

B.4.3.2.4 *Optical detection*

A detector shall be used so that the maximum possible backscattered power should be intercepted. The detector response shall be compatible with the levels and wavelengths of the detected signal. For attenuation measurements the detector response shall be substantially linear.

Signal processing is required to improve the signal to noise ratio, and it is desirable to have a logarithmic response in the detection system.

A suitable amplifier shall follow the optical detector, so that the signal level becomes adequate for the signal processing. The bandwidth of the amplifier will be chosen as a trade-off between time resolution and noise reduction.

figure B-9/G.652, p.

B.4.3.2.5 *Cladding mode stripper*

See § B.2.1.5.

B.4.3.2.6 *Procedure*

1) The fibre under test is aligned to the coupling device.

2) Backscattered power is analyzed by a signal processor and recorded on a logarithmic scale. Figure B-10b/G.652 shows such a typical curve.

3) The attenuation between two points A and B of the curve corresponding to two cross-sections of the fibre is

200.if 409>195 .nr 14 409

A_{AB} t$A(\lambda)$ =

[Formula Deleted]

A — V

B) (dB)

where V_A and V_B are the corresponding power levels given on a logarithmic scale.

Note — Attention must be given to the scattering conditions at points A and B when calculating the attenuation in this way.

4) If so required, bi-directional measurements can be made, together with numerical computation to improve the quality of the result and possibly to allow the separation of attenuation from backscattering factor.

B.4.3.2.7 *Results*

The following details shall be presented:

a) measurement types and characteristics;

b) launching techniques;

c) test set-up arrangement;

d) relative humidity and temperature of the sample (when necessary);

e) fibre identification;

f) length of sample;

g) rise time, width and repetition rate of the pulse;

h) kind of signal processing used;

i) The recorded curve on a logarithmic scale, with the attenuation of the sample, and under certain conditions the attenuation coefficient in dB/km.

Note — The complete analysis of the recorded curve (Figure B-10b/G.652) shows that, independently from the attenuation measurement, many phenomena can be monitored using the backscattering technique:

a) reflection originated by the coupling device at the input end of the fibre;

b) zone of constant slope;

c) discontinuity due to local defect, splice or coupling;

d) reflection due to dielectric defect;

e) reflection at the end of the fibre.

B.4.4 *Second alternative test method: the insertion loss technique*

Under consideration.

B.5 — Section V — *Test methods for chromatic dispersion coefficient measurement*

B.5.1 *Reference test method for chromatic dispersion coefficient measurement*

B.5.1.1 *Objective*

The fibre chromatic dispersion coefficient is derived from the measurement of the relative group delay experienced by the various wavelengths during propagation through a known length of fibre.

figure B-10/G.652, p.12

The group delay can be measured either in the time domain or in the frequency domain, according to the type of modulation of the source.

In the former case the delay experienced by pulses at various wavelengths is measured; in the latter the phase shift of a sinusoidal modulating signal is recorded and processed to obtain the time delay.

The chromatic dispersion may be measured at a fixed wavelength or over a wavelength range.

B.5.1.2 *Test apparatus*

A schematic diagram of the test apparatus is shown in Figure B-11/G.652.

B.5.1.2.1 *Source*

The source shall be stable in position, intensity and wavelength over a time period sufficiently long to complete the measurement procedure. Laser diodes, LEDs or broadband sources, (e.g. an Nd:YAG laser with a Raman fibre) may be used, depending on the wavelength range of the measurement.

In any case, the modulating signal shall be such as to guarantee a sufficient time resolution in the group delay measurement.

B.5.1.2.2 *Wavelength selection*

A wavelength selector is used to select the wavelength at which the group delay is to be measured. Optical switch, monochromator, dispersive devices, optical filters, optical coupler, connectors, etc., may be used, depending on the type of light sources and measurement set-up. The selection may be carried out by switching electrical driving signals for different wavelength light sources. The wavelength selector may be used either at the input or at the output end of the fibre under test.

B.5.1.2.3 *Detector*

The light emerging from the fibre under test, the reference fibre or the optical divider etc., is coupled to a photo detector whose signal-to-noise ratio and time resolution are adequate for the measurement. The detector is followed by a low noise amplifier if needed.

B.5.1.2.4 *Reference channel*

The reference channel may consist of electrical signal line or optical signal line. A suitable time delay generator may be interposed in this channel. In certain cases, the fibre under test itself can be used as the reference channel line.

B.5.1.2.5 *Delay detector*

The delay detector shall measure the delay time or the phase shift between the reference signal and the channel signal. In the case of sinusoidal modulation, a vector voltmeter could be used. In the case of pulse modulation, a high speed oscilloscope or a sampling oscilloscope could be used.

B.5.1.2.6 *Signal processor*

A signal processor can be added in order to reduce the noise and/or the jitter in the measured waveform. If needed, a digital computer can be used for purposes of equipment control, data acquisition and numerical evaluation of the data.

B.5.1.3 *Procedure*

The fibre under test is suitably coupled to the source and to the detector through the wavelength selector or the optical divider, etc. If needed, a calibration of the chromatic delay of the source may be performed. A suitable compromise between wavelength resolution and signal level must be achieved. Unless the fibre under test is also used as the reference channel line, the temperature of the fibre must be sufficiently stable during the measurement.

The time delay or phase shift between the reference signal and the channel signal at the operating wavelength are to be measured by the delay detector. Data processing appropriate to the type of modulation is used in order to obtain the chromatic dispersion coefficient at the operating wavelength. When needed, a spectral scan of the group delay versus wavelength can be performed; from the measured values a fitting curve can be completed.

The measured group delay per unit fibre length versus wavelength shall be fitted by the quadratic expression:

$$\tau(\lambda) = \tau_0 +$$
[Formula Deleted]
$$(\lambda - \lambda_0)^2$$

where τ_0 is the relative delay minimum at the zero-dispersion wavelength λ_0. The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated quadratic expression:

$$D(\lambda) = (\lambda - \lambda_0)S_0$$

where S_0 is the (uniform) zero-dispersion slope, i.e., the value of the dispersion slope $S(\lambda) = dD/d\lambda$ at λ_0.

Note 1 — These equations for $\tau(\lambda)$ and $D(\lambda)$ are sufficiently accurate over the 1500-1600 nm range. They are not meant to be used in the 1300 nm region.

Note 2 — Alternatively, the chromatic dispersion coefficient can be measured directly, for example by the differential phase shift method. In this case, a straight line shall be fitted directly to the dispersion coefficient for determining λ_0 and S_0.

B.5.1.4 *Presentation of results*

The following details shall be presented:

a) test set-up arrangement;

b) type of modulation used;

c) source characteristics;

d) fibre identification and length;

e) characteristics of the wavelength selector (if present);

f) type of photodetector;

g) characteristics of the delay detector;

h) values of the zero-dispersion wavelength and the zero-dispersion slope.

If the frequency domain technique is used, the time group delay τ will be deduced from the corresponding phase shift ϕ through the relation $\tau = \phi/(2\pi f)$, f being the modulation frequency;

i) fitting procedures of relative delay data with the used fitting wavelength range;

j) temperature for the sample and environment conditions (if necessary).

Figure B-11/G.652, p.

B.5.2 *Alternative test method for chromatic dispersion coefficient measurement: the interferometric test method*

B.5.2.1 *Objective*

The interferometric test method allows the dispersion to be measured, using a short piece of fibre (several metres). This offers the possibility of measuring the longitudinal chromatic dispersion homogeneity of optical fibres. Moreover, it is possible to test the effect of overall or local influences, such as temperature changes and macrobending losses, on the chromatic dispersion.

According to the interferometric measuring principle, the wavelength-dependent time delay between the test sample and the reference path is measured by a Mach-Zehnder interferometer. The reference path can be an air path or as a single-mode fibre with known spectral group delay.

It should be noted that the extrapolation of the chromatic dispersion values derived from the interferometric test on fibres of a few metres length, to long fibre sections assumes longitudinal homogeneity of the fibre. This assumption may not be applicable in every case.

B.5.2.2 *Test apparatus*

Schematic diagrams of the test apparatus using a reference fibre and an air path reference are shown in Figures B-12/G.652 and B-13/G.652 respectively.

B.5.2.2.1 *Optical source*

The source should be stable in position, intensity and wavelength for a time period sufficiently long to complete the measurement procedure. The source must be suitable, e.g. a YAG laser with a Raman fibre or a lamp and LED optical sources etc. For the application of lock-in amplification techniques, a light source for low-frequency modulation (50 to 500 Hz) is sufficient.

B.5.2.2.2 *Wavelength selector*

A wavelength selector is used to select the wavelength at which the group delay is measured. A monochromator, optical interference filter, or other wavelength selector may be used depending on the type of optical sources and measurement systems. The wavelength selector may be used either at the input or the output end of the fibre under test.

The spectral width of the optical sources is to be restricted by the dispersion measuring accuracy, and it is about 2 to 10 nm.

B.5.2.2.3 *Optical detector*

The optical detector must have a sufficient sensitivity in that wavelength range in which the chromatic dispersion has to be determined. If necessary, the received signal has to be upgraded, with for example a transimpedance circuit.

B.5.2.2.4 *Test equipment*

For the recording of the interference patterns, a lock-in amplifier may be used. Balancing of the optical length of the two ways of the interferometer is performed with one linear positioning device in the reference path. Concerning the positioning device, attention should be paid to the accuracy, uniformity and stability of linear motion. The variation of the length should cover the range from 20 to 100 mm with an accuracy of about 2 μm.

B.5.2.2.5 *Specimen*

The specimen for the test can be uncabled and cabled single-mode fibres. The length of the specimen should be in the range 1 m to 10 m. The accuracy of the length should be about ± | mm. The preparation of the fibre endfaces should be carried out with reasonable care.

B.5.2.2.6 *Data processing*

For the analysis of the interference patterns, a computer with suitable software should be used.

B.5.2.3 *Test procedure*

1) The fibre under test is placed in the measurement set-up (Figures B-12/G.652, B-13/G.652). The positioning of the endfaces is carried out with 3-dimensional micro-positioning devices by optimizing the optical power received by the detector. Errors arising from cladding modes are not possible.

2) The determination of the group delay is performed by balancing the optical lengths of the two interferometer paths with one linear positioning device in the reference path for different wavelengths. The difference between position x_i of the maximum of the interference pattern for wavelength λ_i and position x_0 (Figure B-14/G.652) determines the group delay difference ?63t_g (λ_i) between the reference path and the test path as follows:

$$t_g(\lambda_i) = \frac{x_0 - x_i}{c_0}$$

where c_0 | is the velocity of light in the vacuum. The group delay of the test sample is calculated by adding the value ?63t_g (λ_i) and the spectral group delay of the reference path. Dividing this sum by the test fibre length then gives the measured group delay per unit length $\tau(\lambda)$ of the test fibre.

Figure B-12/G.652, p.14

Figure B-13/G.652, p.15

Figure B-14/G.652, p.16

The measured group delay per unit fibre length versus wavelength shall be fitted by the quadratic expression

$$\tau(\lambda) = \tau_0 + \text{[Formula Deleted]} (\lambda - \lambda_0)^2$$

where τ_0 | is the relative delay minimum at the zero-dispersion wavelength λ_0. The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated quadratic expression:

$$D(\lambda) = (\lambda - \lambda_0)S_0$$

where S_0 is the (uniform) zero-dispersion slope, i.e., the value of the dispersion slope $S(\lambda) = dD/d\lambda$ at λ_0.

Note — These equations for $\tau(\lambda)$ and $D(\lambda)$ are sufficiently accurate over the 1500-1600 nm range. They are not meant to be used in the 1300 nm region.

B.5.2.4 *Presentation of results*

The following details shall be presented:

a) test set-up arrangement;

b) source characteristics;

c) fibre identification and length;

d) characteristics of the wavelength selector (if present);

e) type of the photodetector;

f) values of the zero-dispersion wavelength and the zero-dispersion slope;

g) fitting procedures of relative delay date with the used fitting wavelength range;

h) temperature of the sample and environmental conditions (if necessary).

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