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DEFINITION AND TEST METHODS FOR THE RELEVANT PARAMETERS OF SINGLE-MODE FIBRES

ITU-T Recommendation G.650

(Previously "CCITT Recommendation")

FOREWORD

The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of the International Telecommunication Union. The ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Conference (WTSC), which meets every four years, established the topics for study by the ITU-T Study Groups which, in their turn, produce Recommendations on these topics.

ITU-T Recommendation G.650 was prepared by the ITU-T Study Group XV (1988-1993) and was approved by the WTSC (Helsinki, March 1-12, 1993).

NOTES

1 As a consequence of a reform process within the International Telecommunication Union (ITU), the CCITT ceased to exist as of 28 February 1993. In its place, the ITU Telecommunication Standardization Sector (ITU-T) was created as of 1 March 1993. Similarly, in this reform process, the CCIR and the IFRB have been replaced by the Radiocommunication Sector.

In order not to delay publication of this Recommendation, no change has been made in the text to references containing the acronyms "CCITT, CCIR or IFRB" or their associated entities such as Plenary Assembly, Secretariat, etc. Future editions of this Recommendation will contain the proper terminology related to the new ITU structure.

2 In this Recommendation, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

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Recommendation G.650

DEFINITION AND TEST METHODS FOR THE RELEVANT PARAMETERS OF SINGLE-MODE FIBRES

(Helsinki, 1993)

The CCITT,

considering that

(a) single-mode fibres of different designs are widely used in telecommunication networks;

(b) three Recommendations (namely G.652, G.653 and G.654) concerning different optical fibre cables have already been issued;

(c) the definition of the relevant parameters given in these Recommendations, as well as the test methods to verify the various characteristics, are intimately connected to the Recommendations themselves;

(d) these definitions and test methods differ among the various Recommendations only by a few details;

(e) new Recommendations concerning single-mode fibre cables of different design could be issued in the future, referring substantially to the same definitions and test methods,

recommends

the definitions of the relevant parameters listed in 1, and the test methods for said parameters described in 2, to be followed for single-mode fibre cables covered by Recommendations G.652, G.653 and G.654.

1 Definition of the relevant parameters for single-mode fibres

For the purpose of this Recommendation the following definitions apply:

1.1 General definitions

1.1.1 refractive index profile: the refractive index along a diameter of the fibre.

1.1.2 reference test method (RTM): a test method in which a given characteristic of a specified class of optical fibres or optical fibre cables is measured strictly according to the definition of this characteristic and which gives results which are accurate, reproducible and relatable to practical use.

1.1.3 alternative test method (ATM): a test method in which a given characteristic of a specified class of optical fibres or optical fibre cables is measured in a manner consistent with the definition of this characteristic and gives results which are reproducible and relatable to the reference test method and to practical use.

1.1.4 cladding mode stripper: a device or material that encourages the conversion of cladding modes to radiation modes.

1.1.5 mode filter: a device designed to accept or reject a certain mode or modes.

1.2 Mechanical characteristics

1.2.1 primary coating: the one or more layers of protective coating material applied to the fibre cladding during or after the drawing process to preserve the integrity of the cladding surface and to give a minimum amount of required protection (e.g. a 250 μm protective coating).

1.2.2 secondary coating: the one or more layers of coating material applied over one or more primary coated fibres in order to give additional required protection or to arrange fibres together in a particular structure (e.g. a 900 μm “buffer” coating, “tight jacket”, or a ribbon coating).

1.2.3 prooftest level: the prooftest level is the specified value of tensile stress or strain to which a full length of fibre is subjected for a specified short time period. This is usually done sequentially along the fibre length.

1.2.4 stress corrosion parameter: the stress corrosion (susceptibility) parameter n is a dimensionless coefficient empirically related to the dependence of crack growth on applied stress. It depends upon the ambient temperature, humidity and other environmental conditions.

Both a static and a dynamic value for this parameter can be given.

The static value n_s is the negative of the slope of a static fatigue log-log plot of failure time versus applied stress.

The dynamic value is n_d where $1/(n_d + 1)$ is the slope of a dynamic fatigue log-log plot of failure stress versus applied stress rate.

NOTE – n need not be an integer.

1.3 Mode field characteristics

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

1.3.2 mode field diameter: the mode field diameter (MFD) $2w$ is defined from the far-field intensity distribution $F^2(q)$ [$q = (\lambda/\lambda) \cdot \sin\theta$, θ being the far-field angle and λ the wavelength], through the following equation:

$$2w = (2/\pi)\,[2 \int_0^\infty q^3 F^2(q)\,dq \;/\; \int_0^\infty qF^2(q)\,dq]^{-1/2} \qquad (1\text{-}1)$$

The integration limits are shown to be 0 to ∞, but it is understood that this notation implies that the integral be truncated in the limit of increasing argument. While the maximum physical value of the argument q is $1/\lambda$, the integrand rapidly approach zero before this value is reached.

NOTE – Such a definition is strictly related to a measurement configuration based on the far-field scan. Equivalent equations for the MFD can be derived from Eq. (1-1) in case of the following alternative measurement configurations:

1) *variable aperture technique:* let $\alpha(x)$ be the complementary aperture transmission function ($x = D \cdot \tan\theta$ being the aperture radius, and D the distance between the aperture and the fibre), then the MFD results:

$$2w = (2/\pi)\,[4 \int_0^\infty \alpha(x)\, q\,dq]^{-1/2} \qquad (1\text{-}2)$$

2) *knife-edge scan:* let $K(x)$ be the knife-edge power transmission function ($x = D \cdot \tan\theta$ being the knife-edge lateral offset, and D the distance between the knife-edge and the fibre), then the MFD results:

$$2w = (2/\pi)\,[4 \int_0^\infty [dK(x)/dx]q^2\,dq \;/\; \int_0^\infty [dK(x)/dx]\,dq]^{-1/2} \qquad (1\text{-}3)$$

3) *near-field scan*: let $f^2(r)$ be the near-field intensity distribution (r being the radial coordinate), then the MFD results:

$$2w = 2\,[2 \int_0^\infty rf^2(r)\,dr \;/\; \int_0^\infty r\,[df(r)/dr]^2\,dr]^{1/2} \qquad (1\text{-}4)$$

The mathematical equivalence of these definitions results from transform relations among the distributions or functions obtained on the different measurement configurations. These are summarized in Figure 1.

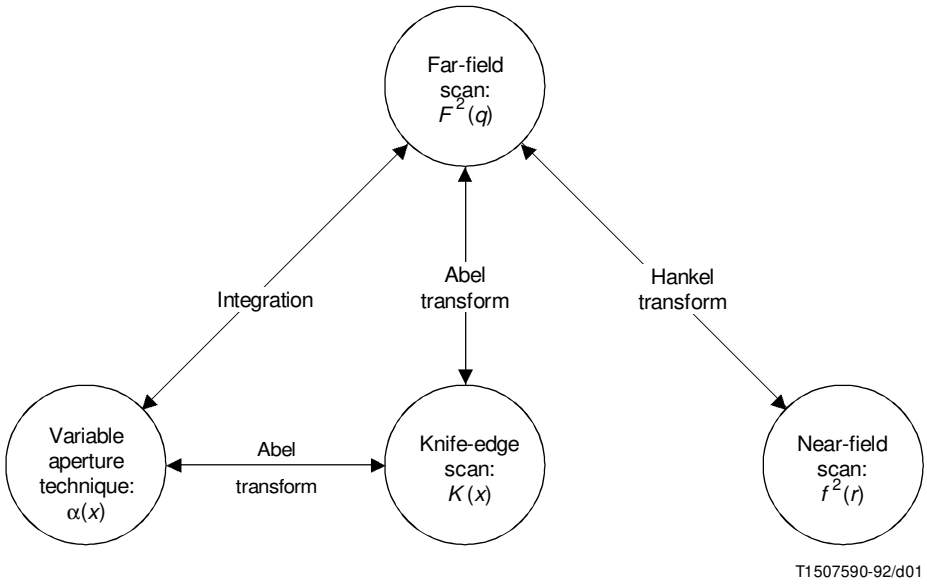


FIGURE 1/G.650

Mathematical relations between measurement implementations

1.3.3 **mode field centre**: the mode field centre is the position of the centroid of the spatial intensity distribution in the fibre.

NOTES

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

$$\vec{r}_c = \iint_{\text{AREA}} \vec{r} I(\vec{r})\, \text{dA} \,/\, \iint_{\text{AREA}} I(\vec{r})\, \text{dA} \qquad (1\text{-}5)$$

2 The correspondence between the position of the centroid as defined and the position of the maximum of the spatial intensity distribution requires further study.

1.3.4 **mode field concentricity error**: the distance between the mode field centre and the cladding centre.

1.3.5 **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/G.652, G.653 and G.654) a definition of mode field non-circularity is not necessary in this context.

1.4 Cladding characteristics

1.4.1 **cladding**: the outermost region of constant refractive index in the fibre cross-section.

1.4.2 **cladding centre**: for a cross-section of an optical fibre it is the centre of that circle which best fits the outer limit of the cladding.

NOTE – The method of best fitting has to be specified. One possible method is described in Appendix I of Section I of Annex B/G.651.

1.4.3 **cladding diameter**: the diameter of the circle defining the cladding centre.

1.4.4 **cladding diameter deviation**: the difference between the actual and the nominal values of the cladding diameter.

1.4.5 **cladding tolerance field**: for a cross-section of an optical fibre it is the region between the circle circumscribing the outer limit of the cladding, and the largest circle, concentric with the first one, that fits into the outer limit of the cladding. Both circles shall have the same centre as the cladding.

1.4.6 cladding non-circularity: the difference between the diameters of the two circles defined by the cladding tolerance field divided by the nominal cladding diameter.

1.5 Chromatic dispersion definitions

1.5.1 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.

1.5.2 chromatic dispersion coefficient: the chromatic dispersion per unit source spectrum width and unit length of fibre. It is usually expressed in ps/(nm · km).

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

1.5.4 zero-dispersion wavelength: that wavelength at which the chromatic dispersion vanishes.

1.5.5 source wavelength offset: (for G.653 fibres only) the absolute difference between the source operating wavelength and 1550 nm.

1.5.6 dispersion offset: (for G.653 fibres only) the absolute displacement of the zero-dispersion wavelength from 1550 nm.

1.6 Other characteristics

1.6.1 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.

NOTES

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. According to this definition, the LP_{11} mode attenuation in the test sample is 19.3 dB at the cut-off wavelength.

2 The cut-off wavelength defined in this Recommendation is generally different from the theoretical 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.

3 In 1.5/G.652, 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 λ_{cc} measured in a cabled fibre in a deployment condition.

To avoid modal noise and dispersion penalties, the cut-off wavelength λ_{cc} of the shortest cable length (including repair lengths when present) should be less than the lowest anticipated system wavelength, λ_s:

$$\lambda_{cc} < \lambda_s \tag{1-6}$$

This ensures that each individual cable section is sufficiently single mode. Any joint that is not perfect will create some higher order (LP_{11}) 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_{11} mode before it reaches the next joint. If inequality (1-6) 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 $\lambda_{cc} < \lambda_s$ 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 λ_{cc}, in addition, depends on the structure of a particular cable. The relationship between λ_c and λ_{cc}, therefore, is dependent on both the fibre and cable designs. In general λ_c is several tens of nm larger than λ_{cc}; λ_c can even be larger than the system wavelength, without violating inequality (1-6). Higher values of λ_c produce tighter confinement of the LP_{01} mode and, therefore, help to reduce potential bending losses in the 1550 nm wavelength region.

Short fibre lengths (< 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.

Between these, option a) is addressed in Recommendations G.652, G.653 and G.654.

1.6.2 attenuation: the attenuation $A(\lambda)$ at wavelength λ between two cross sections 1 and 2 separated by distance L of a fibre is defined, as:

$$A(\lambda) = 10 \log [P_1(\lambda) / P_2(\lambda)] \quad \text{(dB)} \tag{1-7}$$

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 independent of the length of the fibre:

$$\alpha(\lambda) = A(\lambda) / L \quad \text{(dB/unit length)} \tag{1-8}$$

2 Test methods for single-mode fibres

Both reference test method (RTM) and alternative test methods (ATMs) are usually given here 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.

NOTE – The apparatus and procedure given cover only the essential basic features of the test methods. It is assumed that the detailed instrumentation will incorporate all necessary measures to ensure stability, noise elimination, signal-to-noise ratio, etc.

2.1 Test methods for the mode field diameter

2.1.1 Reference test method: The far-field scan

2.1.1.1 General

The mode field diameter is determined from the far-field intensity distribution $F^2(q)$ according to the definition shown in 1.3.2.

2.1.1.2 Test apparatus

2.1.1.2.1 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.

2.1.1.2.2 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 with the source modulation frequency. The detecting system should have substantially linear sensitivity characteristics.

2.1.1.2.3 Launching conditions

The launching conditions used must be sufficient to excite the fundamental (LP_{01}) 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.

2.1.1.2.4 Cladding mode stripper

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

2.1.1.2.5 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 the fibre axes. It is recommended that the end faces be flat and perpendicular to the fibre axes to within 1°.

2.1.1.2.6 Scan apparatus

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 detector should be at least 10 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 $2wb/\lambda$, 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 minimum dynamic range of the measurement should be 50 dB. This corresponds to a maximum scan half-angle of 20° and 25°, or greater, for fibres covered by Recommendation G.652 and Recommendation G.653, respectively.

NOTES

1 Reducing such dynamic range (or maximum scan half-angle) requirements may introduce errors. For example, restricting those values to 30 dB and 12.5° for G.652 fibres, and to 40 dB and 20° for G.653 fibres, may result in a relative error, in the determination of the MFD, greater than 1%.

2 For G.654 fibres the same considerations as for G.652 fibres apply.

2.1.1.2.7 Detector

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

2.1.1.2.8 Amplifier

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

2.1.1.2.9 Data acquisition

The measured signal level shall be recorded and suitably processed.

2.1.1.3 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.

The following procedure shall be followed: 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 Eq. (1-1).

2.1.1.4 Presentation of the results

The following details shall be presented:

a) Test set-up arrangement, dynamic range of the measurement system, processing algorithms, and a description of the scanning device used (including the scan angle).

b) Launching conditions.

c) Wavelength and spectral linewidth FWHM of the source.

d) Fibre identification and length.

e) Type of cladding mode stripper.

f) Type and dimensions of the detector.

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

h) Indication of the accuracy and repeatability.

i) Mode field diameter.

2.1.2 First alternative test method: The variable aperture technique

2.1.2.1 General

The mode field diameter is determined from the complementary power transmission function $\alpha(x)$ according to 1.3.2.

2.1.2.2 Test apparatus

2.1.2.2.1 Light source (as in 2.1.1.2.1)

2.1.2.2.2 Modulation (as in 2.1.1.2.2)

2.1.2.2.3 Launching conditions (as in 2.1.1.2.3)

2.1.2.2.4 Cladding mode stripper (as in 2.1.1.2.4)

2.1.2.2.5 Specimen (as in 2.1.1.2.5)

2.1.2.2.6 Aperture apparatus

A mechanism containing at least twelve apertures spanning the half-angle range of numerical apertures from 0.02 to 0.25 (0.4 for fibres covered by Recommendation G.653) should be used. Light transmitted by the aperture is collected and focused onto the detector.

NOTE – The NA of the collecting optics must be large enough not to affect the measurement results.

2.1.2.2.7 Detector (as in 2.1.1.2.7)

2.1.2.2.8 Amplifier (as in 2.1.1.2.8)

2.1.2.2.9 Data acquisition (as in 2.1.1.2.9)

2.1.2.3 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.

The following procedure shall be followed: the power transmitted by each aperture, $P(x)$, is measured, and the complementary aperture transmission function, $\alpha(x)$, is found as:

$$\alpha(x) = 1 - \frac{P(x)}{P_{max}} \qquad (2\text{-}1)$$

where P_{max} is the power transmitted by the largest aperture and x is the aperture radius. The mode field diameter is computed from Eq. (1-2).

2.1.2.4 Presentation of the results

The following details shall be presented:

a) Test set-up arrangement, dynamic range of the measurement system, processing algorithms, and a description of the aperture assembly used (including the NA).

b) Launching conditions.

c) Wavelength and spectral linewidth FWHM of the source.

d) Fibre identification and length.

e) Type of cladding mode stripper.

f) Type and dimensions of the detector.

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

h) Indication of the accuracy and repeatability.

i) Mode field diameter.

2.1.3 Second alternative test method: The knife-edge scan

2.1.3.1 General

The mode field diameter is determined from the knife-edge transmission function $K(x)$ according to 1.3.2.

2.1.3.2 Test apparatus

2.1.3.2.1 Light source (as in 2.1.1.2.1)

2.1.3.2.2 Modulation (as in 2.1.1.2.2)

2.1.3.2.3 Launching conditions (as in 2.1.1.2.3)

2.1.3.2.4 Cladding mode stripper (as in 2.1.1.2.4)

2.1.3.2.5 Specimen (as in 2.1.1.2.5)

2.1.3.2.6 Scan apparatus

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. For fibres covered by Recommendation G.653 the collection optics should have an NA of 0.4 or greater.

NOTE – The NA of the collecting optics must be large enough not to affect the measurement results.

2.1.3.2.7 Detector (as in 2.1.1.2.7)

2.1.3.2.8 Amplifier (as in 2.1.1.2.8)

2.1.3.2.9 Data acquisition (as in 2.1.1.2.9)

2.1.3.3 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.

The following procedure shall be followed: 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 Eq. (1-3).

2.1.3.4 Presentation of the results

The following details shall be presented:

a) Test set-up arrangement, dynamic range of the measurement system, processing algorithms, and a description of the scanning device used (including the NA).

b) Launching conditions.

c) Wavelength and spectral linewidth FWHM of the source.

d) Fibre identification and length.

e) Type of cladding mode stripper.

f) Type and dimensions of the detector.

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

h) Indication of the accuracy and repeatability.

i) Mode field diameter.

2.1.4 Third alternative test method: The near-field scan

2.1.4.1 General

The mode field diameter is determined from the near-field intensity distribution $f^2(r)$ according to 1.3.2.

2.1.4.2 Test apparatus

2.1.4.2.1 Light source (as in 2.1.1.2.1)

2.1.4.2.2 Modulation (as in 2.1.1.2.2)

2.1.4.2.3 Launching conditions (as in 2.1.1.2.3)

2.1.4.2.4 Cladding mode stripper (as in 2.1.1.2.4)

2.1.4.2.5 Specimen (as in 2.1.1.2.5)

2.1.4.2.6 Scan apparatus

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 independently known with sufficient accuracy.

2.1.4.2.7 Detector (as in 2.1.1.2.7)

2.1.4.2.8 Amplifier (as in 2.1.1.2.8)

2.1.4.2.9 Data acquisition (as in 2.1.1.2.9)

2.1.4.3 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.

The following procedure shall be followed: 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 Eq. (1-4). 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 Eq. (1-1).

2.1.4.4 Presentation of the results

The following details shall be presented:

a) Test set-up arrangement, dynamic range of the measurement system, processing algorithms, and a description of the imaging and scanning devices used.

b) Launching conditions.

c) Wavelength and spectral linewidth FWHM of the source.

d) Fibre identification and length.

e) Type of cladding mode stripper.

f) Magnification of the apparatus.

g) Type and dimensions of the detector.

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

i) Indication of the accuracy and repeatability.

j) Mode field diameter.

2.2 Test methods for the cladding diameter, mode field concentricity error and cladding non-circularity

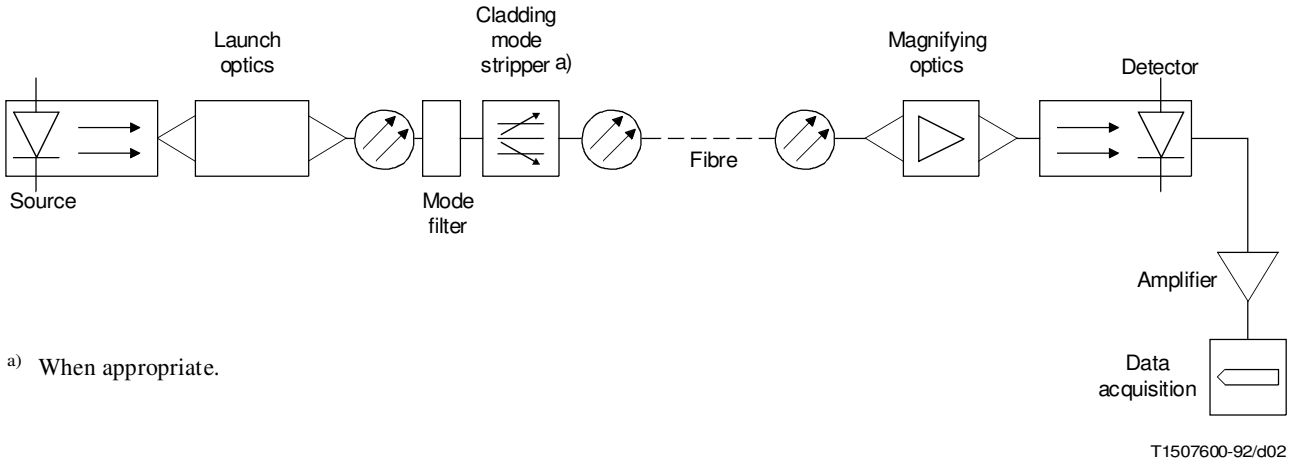
2.2.1 Reference test method: The transmitted near-field technique

2.2.1.1 General

The geometrical parameters are determined from the near-field intensity distribution according to the definitions given in 1.3.4, 1.4.3 and 1.4.6.

2.2.1.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure 2.



a) When appropriate.

FIGURE 2/G.650

Typical arrangement of the transmitted near field set-up

2.2.1.2.1 Light source

A nominal 1310 nm or 1550 nm, for fibres covered by Recommendation G.652 or Recommendations G.653 and G.654, respectively, 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.

2.2.1.2.2 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.

2.2.1.2.3 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.

2.2.1.2.4 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.

2.2.1.2.5 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 the fibre axis.

2.2.1.2.6 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.

2.2.1.2.7 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 of intensities encountered.

2.2.1.2.8 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.

2.2.1.2.9 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.

2.2.1.3 Measurement procedure

2.2.1.3.1 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.

2.2.1.3.2 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.

Algorithms for defining edges and calculating the geometrical parameters are under study.

2.2.1.4 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.

2.2.2 First alternative test method: The refracted near-field technique

2.2.2.1 General

The refractive near-field measurement gives directly the refractive index distribution across the entire fibre (core and cladding). The geometrical characteristics of the fibre can be obtained from the refractive index distribution, using suitable algorithms.

2.2.2.2 Test apparatus

A schematic diagram of the measurement method is shown in Figure 3. The technique involves scanning of a focussed spot of light across the end of the fibre. The launch optics are arranged to overfill the numerical aperture of the fibre. The fibre end is immersed in a fluid of slightly higher index than the cladding. Part of the light is guided down the fibre and the rest appears as a hollow cone outside the fibre. A disc is placed on the axis of the core to ensure that only refracted light reaches the detector.

The optical resolution and hence the ability to resolve details in the fibre geometry depends on the size of the focussed spot of light. This depends both on the numerical aperture of the focussing lens and on the size of the disc. However, the position of sharp features can be resolved to much better accuracy than this, dependent on step size for stepper motor systems, or position monitoring accuracy of analogue drives.

2.2.2.2.1 Source

A stable laser giving about 1 mW of power in the TEM_{00} mode is required, such as a HeNe laser.

A quarter-wave plate is introduced to change the beam from linear to circular polarization because the reflectivity of light at an air-glass interface is strongly angle- and polarization-dependent.

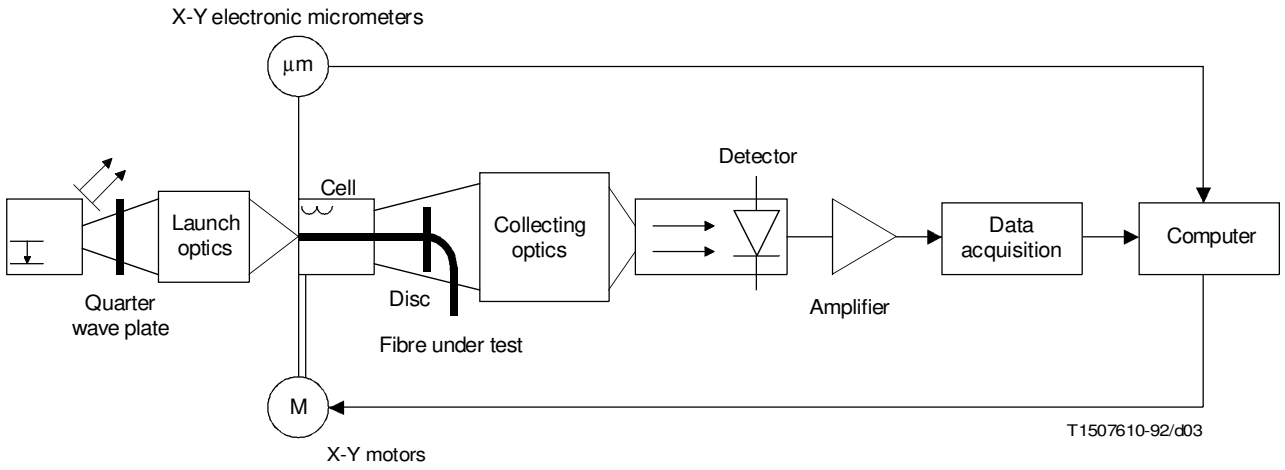


FIGURE 3/G.650

Typical arrangement of the refracted near-field test set-up

2.2.2.2.2 Launching conditions

The launch optics, which are arranged to overfill the numerical aperture of the fibre, bring a beam of light to a focus on the flat end of the fibre. The optical axis of the beam of light should be within 1° of the axis of the fibre. The resolution of the equipment is determined by the size of the focussed spot, which should be as small as possible in order to maximize the resolution, e.g. less than 1.0 µm. The equipment enables the focussed spot to be scanned across the fibre cross-section.

2.2.2.2.3 Cell

The cell will contain a fluid with a refractive index slightly higher than that of the fibre cladding. The position of the cell will be controlled by X-Y motors driven by the computer and detected by X-Y micrometers.

2.2.2.2.4 Detection

The refracted light is collected by suitable collecting optics and brought to the detector in any convenient manner provided that all the refracted light is collected. By calculation the required size of disc and its position along the central axis can be determined.

2.2.2.2.5 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. A computer will be used to drive the X-Y motors, to record the X-Y position of the cell and the corresponding power levels, and to process the measured data.

2.2.2.3 Procedure

Refer to the schematic diagram of the test apparatus (Figure 3).

2.2.2.3.1 Preparation of fibre under test

A length of fibre of about 0.5 m is required.

Primary fibre coating shall be removed from the section of fibre immersed in the fluid cell.

The fibre ends shall be clean, smooth and perpendicular to the fibre axis.

2.2.2.3.2 Equipment calibration

The equipment is calibrated with the fibre removed from the fluid cell. During the measurement the angle of the cone of light varies according to the refractive index seen at the entry point to the fibre (hence the change of power passing the disc). With the fibre removed and the fluid index and cell thickness known, this change in angle can be simulated by translating the disc along the optic axis. By moving the disc to a number of predetermined positions one can scale the profile in terms of relative index. Absolute index can only be found if the cladding or fluid index is known accurately at the measurement wavelength and temperature.

More convenient calibration procedures can be performed by means of a thin rod of known constant refractive index or by means of a multimode-multistep fibre, where the various refractive index values are known with great accuracy. This latter technique can also be useful in checking the linearity of the apparatus. In this respect it may also be useful to control the fluid temperature in the fluid cell.

2.2.2.3.3 Raster scan

The launch end of the fibre to be measured is immersed in the fluid cell and the laser beam is simultaneously centred and focussed on the fibre end face.

The disc is centred on the output cone. Refracted modes passing the disc are collected and focussed onto the detector.

The focussed laser spot is scanned across the fibre end cross-section and a two-dimensional distribution of fibre refractive index is directly obtained. From this distribution the geometrical characteristics will be calculated.

2.2.2.3.4 Geometrical characteristics

Once the raster scan of refractive index is performed, the core contour is obtained taking the points at the core-cladding interface of refractive index coinciding with the mean value between the averaged refractive indices of core and cladding respectively. The cladding contour is determined in a similar way but at the cladding-index matching fluid interface. Geometry analyses consistent with the terms in 1 will be performed starting from the core and cladding contours data. The mode field concentricity error will be evaluated through the core-cladding concentricity error.

2.2.2.4 Presentation of the results

The following details shall be presented:

a) Test set-up arrangement and indication of the scanning technique used.

b) Fibre identification.

c) Cladding diameter.

d) Mode-field concentricity error.

e) Cladding non-circularity.

f) Core diameter (if required).

g) Raster scan across the entire fibre (if required).

h) Indication of accuracy and repeatability.

i) Temperature of the cell and environmental conditions (if necessary).

2.2.3 Second alternative test method: The side-view technique

2.2.3.1 General

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.

2.2.3.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure 4.

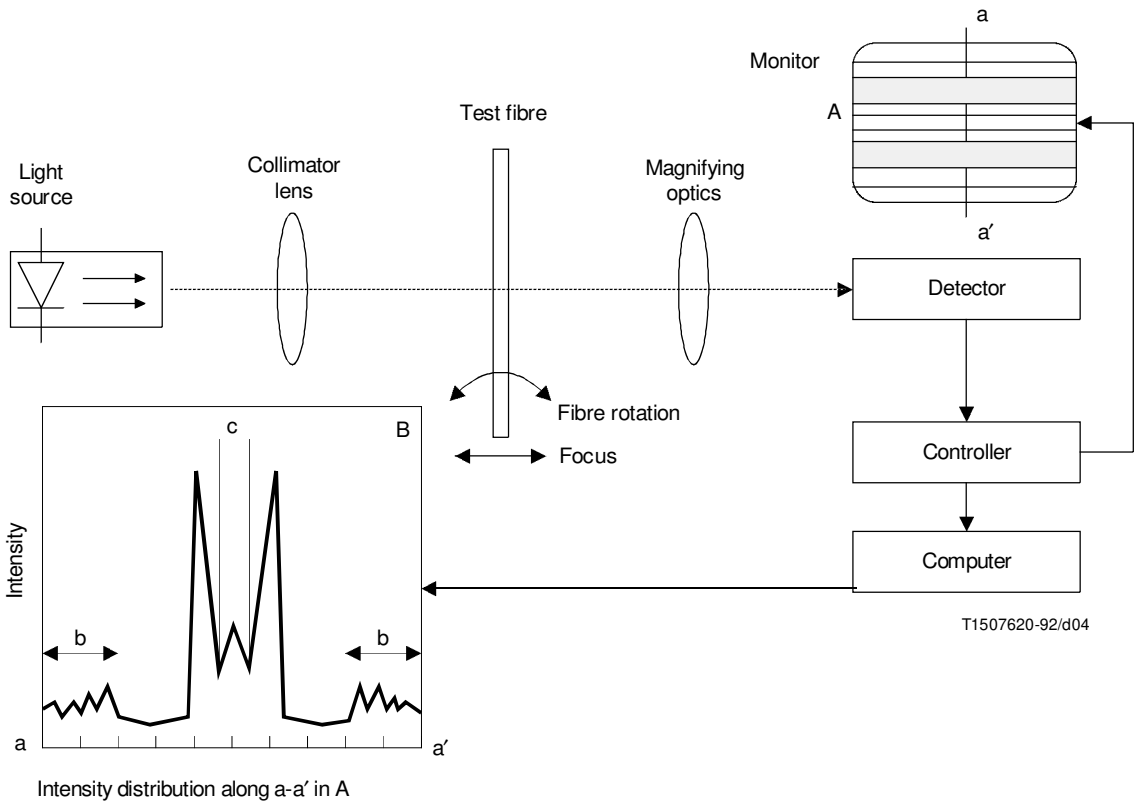


FIGURE 4/G.650

Schematic diagram of side-view measurement system

2.2.3.2.1 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.

2.2.3.2.2 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.

2.2.3.2.3 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.

2.2.3.2.4 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.

2.2.3.2.5 Data processing

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

2.2.3.3 Measurement procedure

2.2.3.3.1 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.

2.2.3.3.2 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 4) 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 analysing the symmetry of the diffraction pattern (shown as b in B). The central position of the core is determined by analysing 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 5, 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.

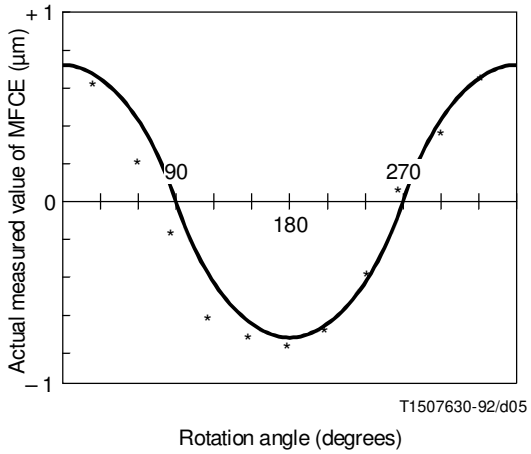


FIGURE 5/G.650

Measured value of the MFCE as a function of rotation angle

2.2.3.4 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 vs rotation angle.

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

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

2.2.4 Third alternative test method: The transmitted near field image technique

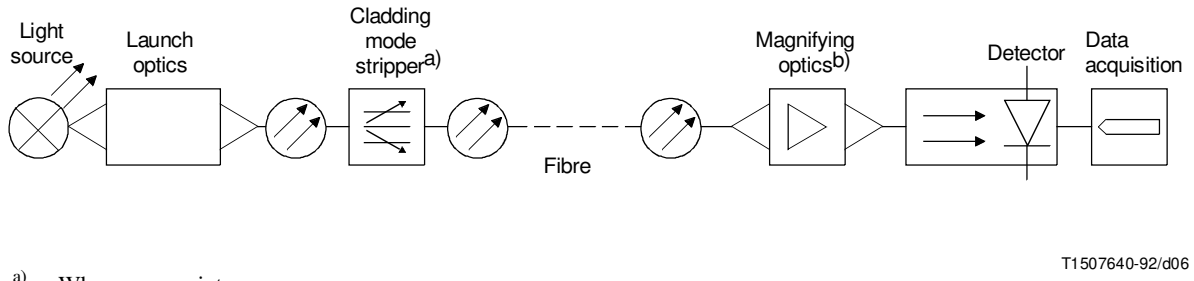
2.2.4.1 General

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.

2.2.4.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure 6.



a) When appropriate.
b) Including image shearing optics, where approriate.

FIGURE 6/G.650

Typical arrangement of the transmitted near field image set-up

2.2.4.2.1 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.

2.2.4.2.2 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.

2.2.4.2.3 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.

2.2.4.2.4 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.

2.2.4.2.5 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.

2.2.4.2.6 Detection

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

a) image shearing;

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

2.2.4.2.7 Data acquisition

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

2.2.4.3 Measurement procedure

2.2.4.3.1 Equipment calibration

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

2.2.4.3.2 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 output 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.

Algorithms for defining edges and calculating the geometrical parameters are under study.

2.2.4.4 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.

2.3 Test methods for the cut-off wavelength

2.3.1 Reference test method for the cut-off wavelength (λ_c) of the primary coated fibre: The transmitted power technique

2.3.1.1 General

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

The transmitted power technique 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.

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.

The measurement may be performed on a fibre having a secondary coating if the secondary coating type has been examined and it has been confirmed that it does not significantly affect the cut-off wavelength, provided that the secondary coating is properly applied.

2.3.1.2 Test apparatus

2.3.1.2.1 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.

2.3.1.2.2 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 with the source modulation frequency. The detecting system should be substantially linear.

2.3.1.2.3 Launching conditions

The launching conditions must be used in such a way as to excite substantially uniformly both LP_{01} and LP_{11} 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.

2.3.1.2.4 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_{11} mode.

2.3.1.2.5 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.

2.3.1.3 Measurement procedure

2.3.1.3.1 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 output power $P_1(\lambda)$ shall be recorded versus λ in a sufficiently wide range around the expected cut-off wavelength.

2.3.1.3.2 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_{11} 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 $P_3(\lambda)$ is measured 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.

2.3.1.3.3 Calculations

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

$$R(\lambda) = 10 \log [P_1(\lambda) / P_i(\lambda)] \quad (2\text{-}2)$$

where $i = 2$ or 3 for 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. $R(\lambda)$ is equal to the logarithmic ratio between the total power emerging from the sample, including the LP_{11} mode power, and the fundamental mode power. When the modes are uniformly excited in accordance with 2.3.1.2.3, $R(\lambda)$ then also yields the LP_{11} mode attenuation $A(\lambda)$ in dB in the test sample:

$$A(\lambda) = 10 \log [(P_1(\lambda) / P_2(\lambda) - 1) / 2] \quad (2\text{-}3)$$

2.3.1.3.4 Determination of cut-off wavelength

If method a) is used, λ_c is determined as the largest wavelength at which $R(\lambda)$ is equal to 0.1 dB (see Figure 7).

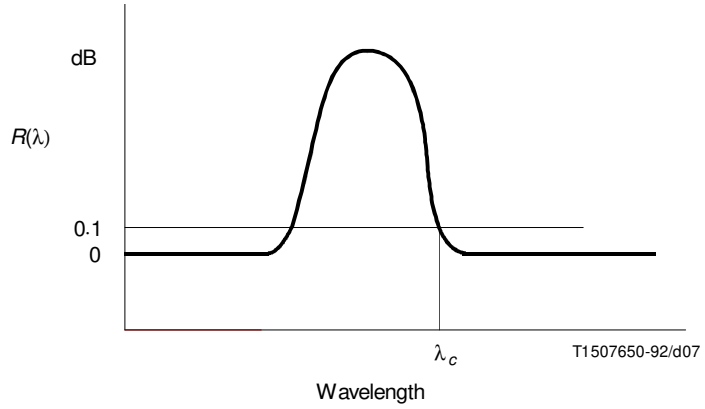


FIGURE 7/G.650

Typical cut-off wavelength plot using single-mode reference

If method b) is used, λ_c 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 8).

NOTE – According to the definition, the LP_{11} mode attenuation in the test sample is 19.3 dB at the cut-off wavelength.

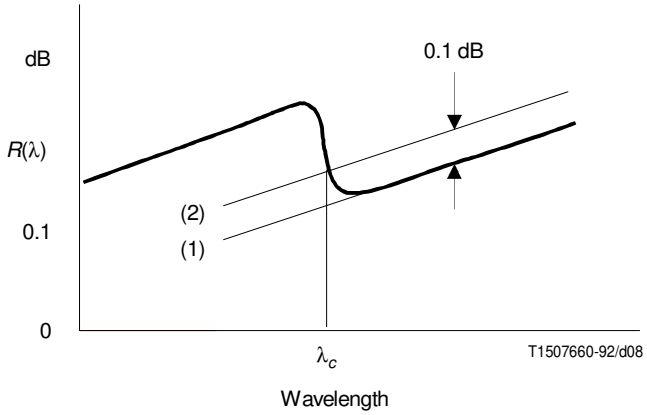


FIGURE 8/G.650

Typical cut-off wavelength plot using multimode reference

2.3.1.4 Presentation of the 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 $R(\lambda)$ (if required).

2.3.2 Alternative test method for λ_c: The split-mandrel technique

2.3.2.1 General (as in 2.3.1.1)

2.3.2.2 Test apparatus

2.3.2.2.1 Light source (as in 2.3.1.2.1)

2.3.2.2.2 Modulation (as in 2.3.1.2.2)

2.3.2.2.3 Launching conditions (as in 2.3.1.2.3)

2.3.2.2.4 Cladding mode stripper (as in 2.3.1.2.4)

2.3.2.2.5 Optical detector (as in 2.3.1.2.5)

2.3.2.3 Measurement procedure

2.3.2.3.1 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 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 9, 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.

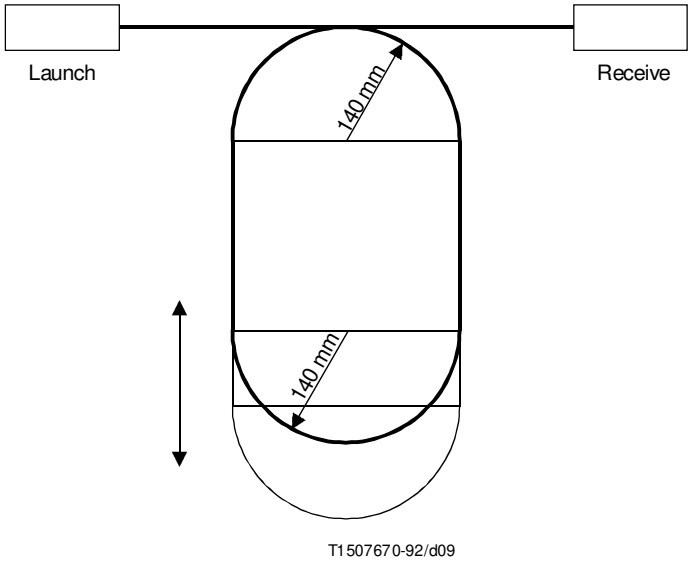


FIGURE 9/G.650

Fibre deployment: Cut-off wavelength by the split-mandrel technique

2.3.2.3.2 Transmission through the reference sample (as in 2.3.1.3.2)

2.3.2.3.3 Calculations (as in 2.3.1.3.3)

2.3.2.3.4 Determination of cut-off wavelength (as in 2.3.1.3.4)

2.3.2.4 Presentation of the results (as in 2.3.1.4)

2.3.3 Reference test method for the cut-off wavelength (λ_{cc}) of the cabled fibres: The transmitted power technique

2.3.3.1 General

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

The transmitted power technique 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.

2.3.3.2 Test apparatus

2.3.3.2.1 Light source (as in 2.3.1.2.1)

2.3.3.2.2 Modulation (as in 2.3.1.2.2)

2.3.3.2.3 Launching conditions (as in 2.3.1.2.3)

2.3.3.2.4 Cladding mode stripper (as in 2.3.1.2.4)

2.3.3.2.5 Optical detector (as in 2.3.1.2.5)

2.3.3.3 Measurement procedure

2.3.3.3.1 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 X = 40 mm radius shall be applied to each uncabled fibre length (see Figure 10). The uncabled fibre is deployed with secondary coating (if present) intact. 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 loops are intended to simulate deployment conditions.

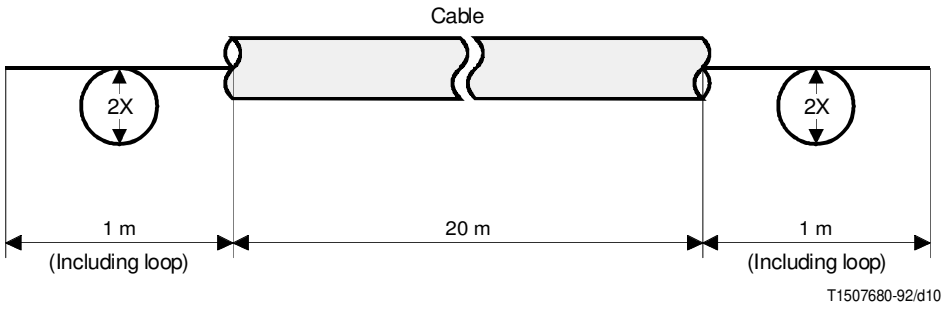


FIGURE 10/G.650

Deployment condition for measurement of the cabled fibre cut-off wavelength

2.3.3.3.2 Transmission through the reference sample (as in 2.3.1.3.2)

2.3.3.3.3 Calculations

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

$$R(\lambda) = 10 \log [P_1(\lambda)/P_i(\lambda)] \quad (2\text{-}4)$$

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

2.3.3.3.4 Determination of cabled fibre cut-off wavelength

If method a) is used, λ_{cc} is determined as the largest wavelength at which $R(\lambda)$ is equal to 0.1 dB (see Figure 7). If method b) is used, λ_{cc} 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 8).

2.3.3.4 Presentation of the 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 and cable identification.

f) Wavelength range of measurement.

g) Cabled fibre cut-off wavelength (if required).

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

2.3.4 Alternative test method for the cut-off wavelength (λ_{cc}) of the cabled fibre

2.3.4.1 General

The cut-off wavelength measurement is performed on uncabled single-mode fibres in a deployment condition which assures that the results for λ_{cc} agree well with those results achieved in measurements conducted on cabled fibres.

This method uses the variation in 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 a smaller radius; or

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

2.3.4.2 Test apparatus

2.3.4.2.1 Light source (as in 2.3.1.2.1)

2.3.4.2.2 Modulation (as in 2.3.1.2.2)

2.3.4.2.3 Launching conditions (as in 2.3.1.2.3)

2.3.4.2.4 Cladding mode stripper (as in 2.3.1.2.4)

2.3.4.2.5 Optical detector (as in 2.3.1.2.5)

2.3.4.3 Measurement procedure

2.3.4.3.1 Standard test sample

The measurement shall be performed on a length of uncabled single-mode fibre. The uncabled fibre is deployed with secondary coating (if present) intact. A fibre length of 22 m is inserted into the test apparatus; the inner 20 m are bent to form loosely constrained loops of a radius $r \geq 140$ mm.

One loop of X = 40 mm radius shall be applied to each fibre end (see Figure 11). The output power $P_1(\lambda)$ shall be recorded versus λ in a sufficiently wide range around the expected cut-off wavelength λ_{cc}.

NOTE – The loops are intended to simulate deployment conditions.

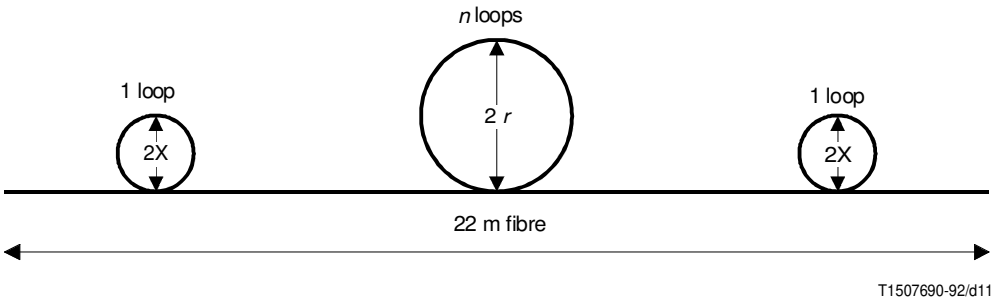


FIGURE 11/G.650

Deployment condition for measurement of l_{cc} on uncabled fibres

2.3.4.3.2 Transmission through the reference sample (as in 2.3.1.3.2)

2.3.4.3.3 Calculations (as in 2.3.1.3.3)

2.3.4.3.4 Determination of cabled fibre cut-off wavelength (as in 2.3.3.3.4)

2.3.4.4 Presentation of the results

As in 2.3.3.4, and in addition:

i) value of *r*.

2.4 Test methods for the attenuation

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.

NOTE – Attenuation values specified for factory lengths should be measured at room temperature (i.e. a single value in the range 10° C to 35° C).

2.4.1 Reference test method: The cut-back technique

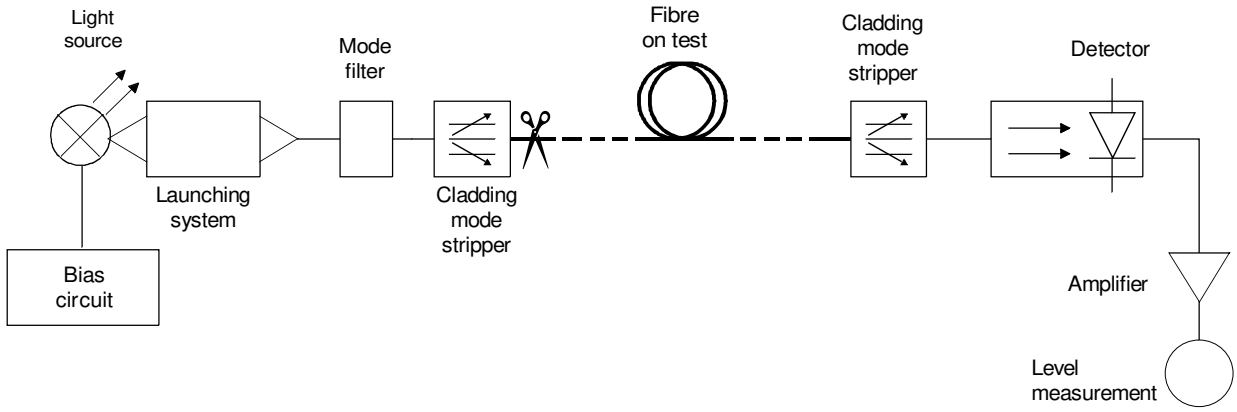
2.4.1.1 General

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.

2.4.1.2 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 equipment, to obtain one loss or the loss spectrum measurements respectively, are shown as examples in Figure l2.

a) Arrangement of test equipment to make one loss measurement



b) Arrangement of test equipment used to obtain the loss spectrum measurement

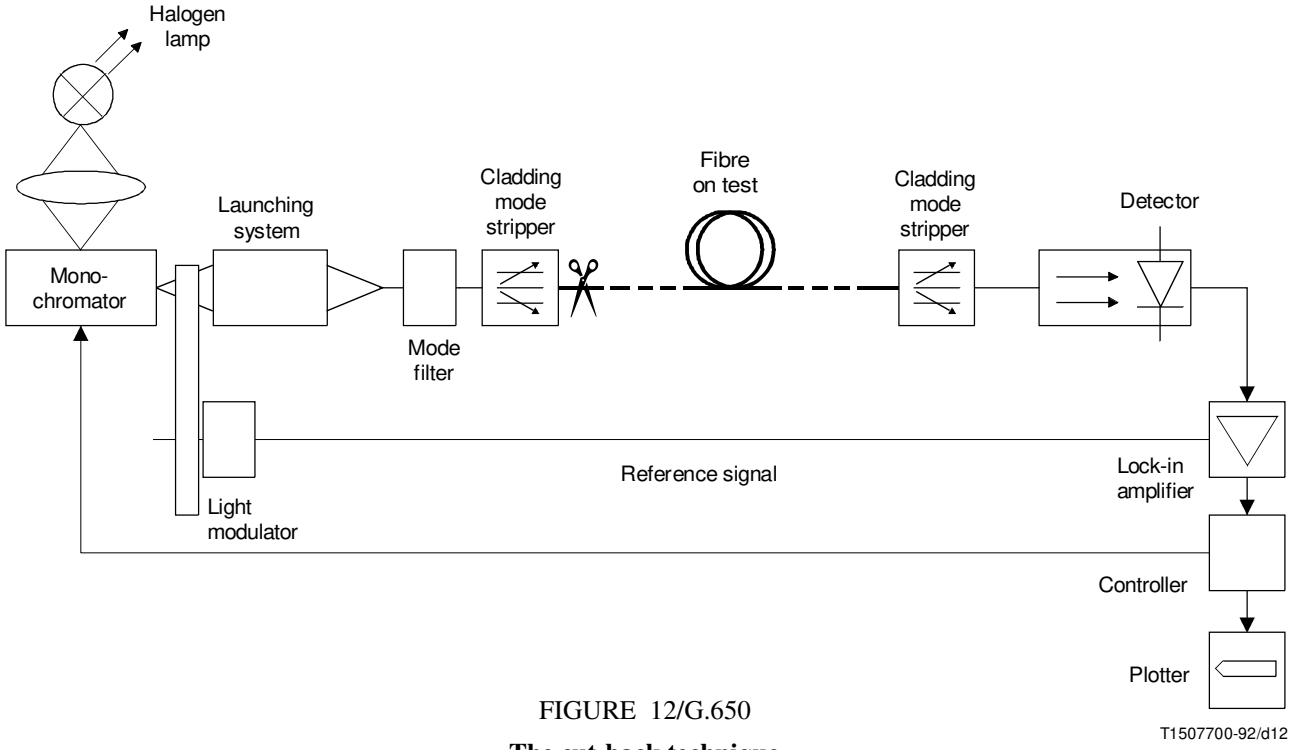


FIGURE 12/G.650

The cut-back technique

2.4.1.2.1 Optical source

A suitable radiation source shall be used 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.

2.4.1.2.2 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 with the source modulation frequency. The detecting system should be substantially linear in sensitivity.

2.4.1.2.3 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.

2.4.1.2.4 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.

2.4.1.2.5 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.

2.4.1.2.6 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 sensitivity characteristics.

2.4.1.3 Measurement procedure

2.4.1.3.1 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.

2.4.1.3.2 Procedure

1) The fibre under test is placed in the measurement 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, using P_1 and P_2, from the definition equations (1-7) and (1-8).

2.4.1.4 Presentation of the 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).

2.4.2 First alternative test method: The backscattering technique

2.4.2.1 General

This test method describes a procedure to measure the attenuation of a homogeneous 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.

2.4.2.2 Test apparatus

2.4.2.2.1 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 the 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 diagram a) of Figure 13.

2.4.2.2.2 Optical source

A stable high power optical source of an appropriate wavelength should be used. The wavelength of the source should be recorded. 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.

2.4.2.2.3 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.

2.4.2.2.4 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.

2.4.2.2.5 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.

2.4.2.2.6 Cladding mode stripper

See 2.4.1.2.5.

2.4.2.3 Measurement procedure

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

2) Backscattered power is analysed by a signal processor and recorded on a logarithmic scale. Diagram b) of Figure l3 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

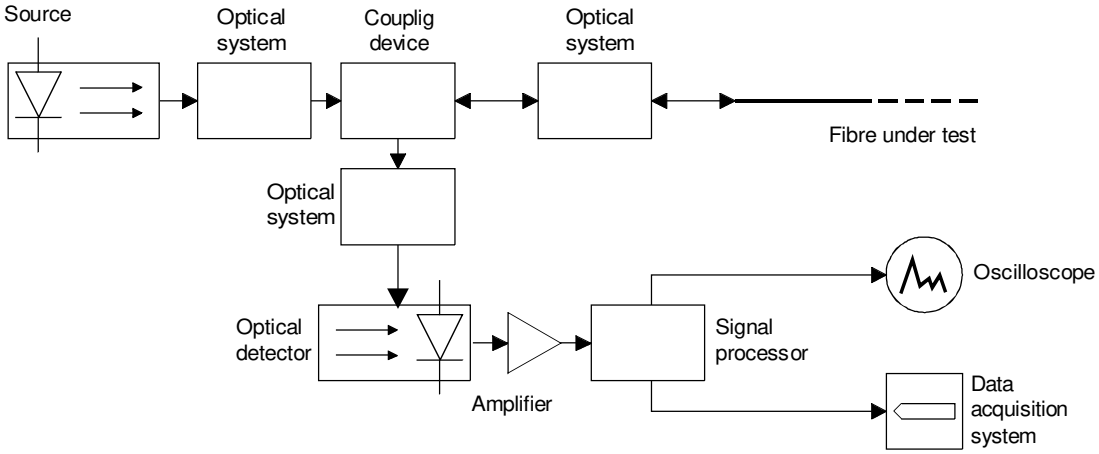
$$A_{A \to B}(\lambda) = \frac{1}{2}\,(V_A - V_B) \quad \text{dB} \tag{2-5}$$

where V_A and V_B are the corresponding power levels given in the 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, bidirectional 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.

a) Schematic of apparatus



b) Example of a backscattered power curve

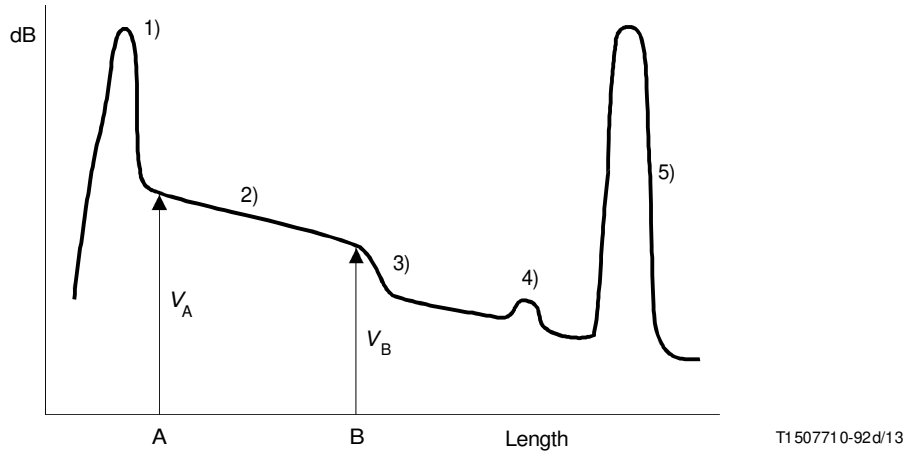


FIGURE 13/G.650

The backscattering technique

2.4.2.4 Presentation of the 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 [diagram b) of Figure 13] shows that, independently from the attenuation measurement, many phenomena can be monitored using the backscattering technique:

1) Reflection originated by the coupling device at the input end of the fibre.

2) Zone of constant slope.

3) Discontinuity due to local defect, splice or coupling.

4) Reflection due to dielectric defect.

5) Reflection at the end of the fibre.

2.4.3 Second alternative test method: The insertion loss technique

2.4.3.1 General

The insertion loss technique consists of the evaluation of the power loss due to the insertion of the fibre under test between a launching and a receiving system, previously interconnected (reference condition). The powers P_1 and P_2 are thus evaluated in a less straightforward way than in the cut-back method. Therefore, this method is not intended for use on factory lengths of fibres and cables.

The insertion loss technique is less accurate than a cut-back one, but has the advantage of being non-destructive for the fibre under test and for the semi-connectors possibly fixed at both ends. Therefore, it is particularly suitable for field use, and mainly intended for use with connectorized cable lengths.

Two options are considered in the following for this technique (see Figure l4); they differ in the nature of the launching and receiving systems, as outlined below. Measurement conditions in between option a) and b) are possible and are discussed in Note 2 to 2.4.3.3.

In option a) the quality of the semi-connectors possibly fixed to the fibre under test (and in general the quality of the used interconnection devices) influences the results; in option b) this influence is nearly excluded.

As a consequence, option b) has in general a better accuracy, and it is more suitable when the actual attenuation of the fibre alone is needed. Conversely, when the fibre section under test is fitted with semi-connectors and has to be cascaded with other elements, the results from option a) are more meaningful, as they take into account the deviation of the semi-connectors from the nominal loss.

2.4.3.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure l4. Measurements may be made at one or more wavelengths, or alternatively, a spectral response may be required over a range of wavelengths.

2.4.3.2.1 Optical source

A suitable intensity stable radiation source shall be used, such as a lamp, a laser or a light emitting diode. If a broad spectrum source is used it should be followed by a wavelength selection device (alternatively this device can be inserted before the detector). In every case the nominal wavelength of the source (possibly taking into account the wavelength selection device) shall be known.

The spectral width (FWHM) should be narrow compared with any features of the fibre spectral attenuation.

2.4.3.2.2 Modulation

See 2.4.1.2.2.

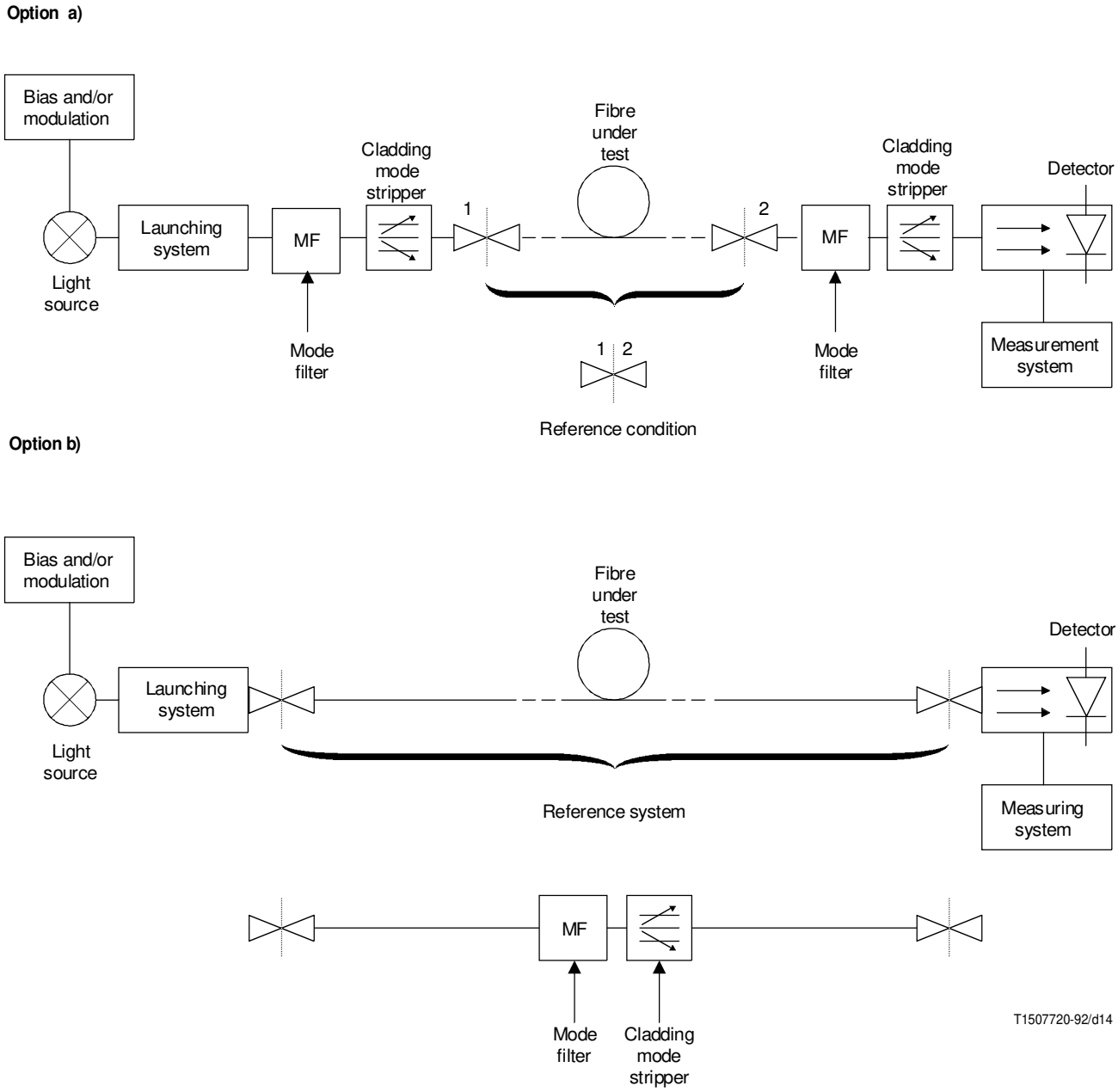


FIGURE 14/G.650

Typical arrangements for the insertion loss technique

2.4.3.2.3 Launching conditions

For option a)

The source is coupled to a short length of single-mode fibre having the same nominal characteristics of the fibre under test and equipped with a mode filter and a cladding mode stripper (see below).

The above single-mode fibre is coupled to the fibre under test with a very precise coupling device to minimize coupling losses and ensure meaningful results. If the fibre under test is equipped with a semi-connector, a compatible high quality semi-connector shall be fixed to the launching fibre.

For option b)

The source is coupled through a suitable optic to the fibre under test in such a way that the launched spot at the fibre input end face has a near field and a far field intensity almost uniform within the mode field diameter and the numerical aperture of the fibre under test.

The system can employ lenses and a fibre positioner; alternatively the light can be launched in a step-index multi-mode fibre to be connected to the fibre under test.

This is accomplished with any coupling device or a semi-connector compatible with those terminating the fibre under test.

2.4.3.2.4 Reference system [option b) only]

This system is composed of a short length of single-mode fibre having the same nominal characteristics of the fibre under test. The fibre is equipped with a mode filter and a cladding mode stripper; both devices shall not introduce any loss on the fundamental mode.

2.4.3.2.5 Mode filter

The mode filter shall allow the propagation along the fibre of the fundamental mode only. As an example it can be implemented by a suitable bending condition on the fibre.

2.4.3.2.6 Cladding mode stripper

A cladding mode stripper encouraging the conversion of cladding modes to radiation modes should be employed. This device is not necessary if the fibre itself does not allow the propagation cladding modes.

2.4.3.2.7 Optical detection

The spectral response of the optical detector shall be compatible with the spectral characteristics of the source. It must have linear sensitivity characteristics.

For option a)

The detector is connected to a single-mode fibre having the same nominal characteristics of the fibre under test. The fibre should be equipped with a mode filter and a cladding mode stripper.

For the coupling with the fibre under test the same indication as in 2.4.3.2.3, option a), is used.

For option b)

The end of the fibre under test is positioned in front of the detector.

A suitable detector shall be used so that all the radiation emerging from the fibre is intercepted. The detector should be spatially uniform.

Alternatively the detector is connected to a step-index multi-mode fibre. This fibre is coupled to the fibre under test by any coupling device or a semi-connector compatible with those terminating the fibre under test.

2.4.3.3 Measurements procedure

2.4.3.3.1 Preparation of the fibre under test

See 2.4.1.3.1.

If the fibre is fitted with connectors, an appropriate cleaning procedure is required.

2.4.3.3.2 Procedure

1) Once a measurement wavelength is selected, the power P_1 is firstly measured in the following way:

For option a)

The fibre of the launching system is connected to the fibre of the receiving system. The received power P_1 is then recorded.

For option b)

The reference system is connected between the launching and the receiving systems. The received power P_1 is then recorded.

2) Successively the fibre under test is connected between the launching and the receiving systems. The received power P_2 is then recorded.

3) Finally the attenuation A of the fibre section is calculated in the following way:

For option a)

$$A = 10 \log (P_1(\lambda)/P_2(\lambda)) + C_r - C_1 - C_2 \quad \text{(dB)} \tag{2-6a}$$

where C_r, C_1, and C_2 are the nominal average losses (in dB) of the connections respectively in the reference conditions at the input of the fibre under test and at its output.

For option b)

$$A = 10 \log (P_1(\lambda)/P_2(\lambda)) \quad \text{(dB)} \tag{2-6b}$$

NOTE 1 – The use of option b) assumes that the fibre under test does not allow the propagation to the receiving end of modes other than the fundamental one.

NOTE 2 – Fibre attenuation measurements are also possible with a hybrid test set-up, using a launching system as in option a) and a receiving system as in option b), or vice versa.

The measurement procedure for P_1 is in both cases similar to the one listed above for option a); no reference system is required and the launching system is connected directly to the receiving system.

In both cases the fibre section attenuation can be calculated as

$$A = 10 \log (P_1(\lambda)/P_2(\lambda)) - C_a \quad \text{(dB)} \tag{2-7}$$

where C_a is the nominal average loss (in dB) of the connection between the fibre under test and that part of the test set-up (launch or receive) belonging to option a).

NOTE 3 – The intrinsic capability of option a) to evaluate the semi-connectors behaviour does not imply its use whenever this evaluation is required.

Alternative possibilities are in using, even at an end where the semi-connector evaluation is required, an option b) set-up, previously connecting a single-mode cord to the fibre under test. The nominal loss of the fibre-to-cord connector is to be subtracted from the measured loss.

The test apparatus to be used in practice should be chosen to minimize the error sources, taking into account the available instrumentation and connecting devices. The use of a hybrid set-up (a-launch, b-receive) plus a cord at the receiving end is usually the best solution when both the semi-connectors have to be evaluated.

2.4.3.4 Presentation of the results

The following details shall be presented:

a) Test set-up arrangement, including source type, source wavelength, spectral width (FWHM) used for the measurement and the option type [a) or b)].

b) Fibre identification.

c) Length of the fibre section and end conditions (presence of semi-connectors).

d) Attenuation of the section quoted in dB.

e) Attenuation coefficient quoted in dB/km.

f) Indication of accuracy and repeatibility (the connection loss repeatibility shall be taken properly into account).

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

2.5 Test methods for the chromatic dispersion

2.5.1 Reference test method: The phase-shift technique

2.5.1.1 General

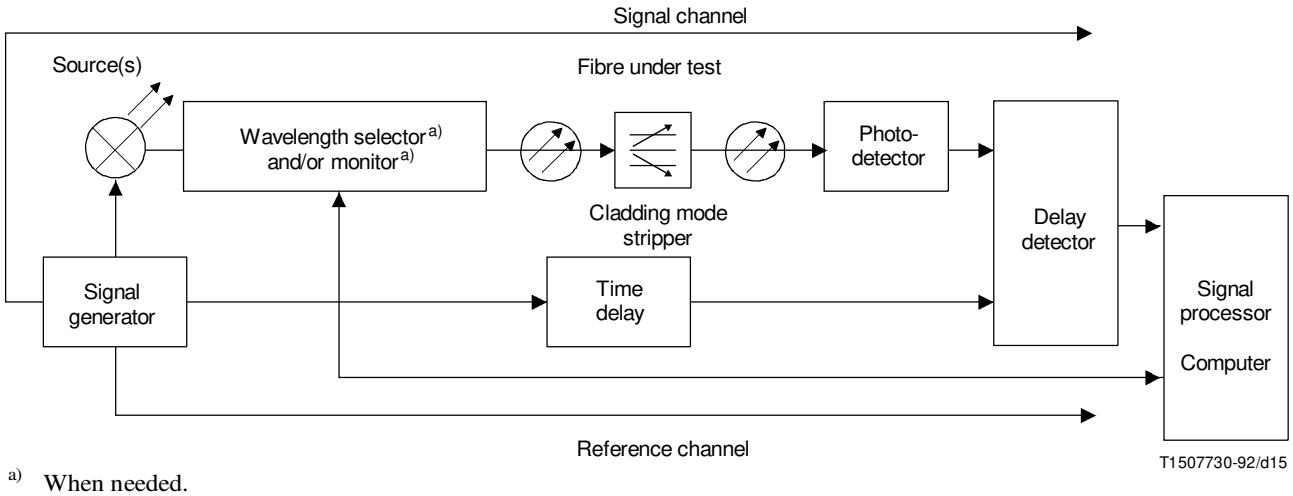
The fibre chromatic dispersion coefficient is derived from the measurement of the relative group delay experienced by the various wavelengths during propagation through a known length of fibre.

The group delay is measured in the frequency domain, by detecting, recording and processing the phase shift of a sinusoidal modulating signal.

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

2.5.1.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure l5.



a) When needed.

FIGURE 15/G.650

Typical arrangement of the test apparatus

2.5.1.2.1 Optical source

The optical source shall be stable in position, intensity and wavelength over a time period sufficiently long to complete the measurement procedure. [Laser diodes, laser diode array (LD-array)], wavelength tuneable laser diodes (WTL) [e.g. an external cavity laser (ECL)], 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.

2.5.1.2.2 Wavelength selection

The wavelength selector and monitoring are used to select and monitor the wavelength at which the group delay is to be measured. As a wavelength selector, an optical switch, a monochromator, dispersive devices, optical filters, optical couplers, connectors 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 monitoring may be carried out by an optical fibre coupler and a wavelength meter. The wavelength selector and monitor may be used either at the input or at the output end of the fibre under test.

2.5.1.2.3 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.

2.5.1.2.4 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.

2.5.1.2.5 Delay detector

The delay detector shall measure the phase shift between the reference signal and the channel signal. A vector voltmeter could be used.

2.5.1.2.6 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.

2.5.1.3 Measurement 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 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 time group delay will be deduced from the corresponding phase shift φ through the relation $t = \varphi/(2\pi f)$, f being the modulation frequency.

2.5.1.3.1 Fibres covered by Recommendation G.652

The measured group delay per unit fibre length versus wavelength shall be fitted by the three-term Sellmeier expression:

$$\tau(\lambda) = \tau_0 + \frac{S_0}{8}\left(\lambda - \frac{\lambda_0^2}{\lambda}\right)^2 \qquad (2\text{-}8)$$

Here 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 Sellmeier expression:

$$D(\lambda) = \frac{S_0}{4}\left(\lambda - \frac{\lambda_0^4}{\lambda^3}\right) \qquad (2\text{-}9)$$

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

NOTES

1 These equations for $\tau(\lambda)$ and $D(\lambda)$ are sufficiently accurate over the 1270-1340 nm range, but are less accurate in the 1550 nm region. Because the dispersion in the latter region is large, the reduced accuracy may be acceptable; if not, it can be improved by including data from the 1550 nm region when performing the fit. However, it should be noted that this may reduce the accuracy in the 1310 nm region.

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

2.5.1.3.2 Fibres covered by Recommendation G.653

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

$$\tau(\lambda) = \tau_0 + \frac{S_0}{2} (\lambda - \lambda_0)^2 \quad (2\text{-}10)$$

Here 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:

$$D(\lambda) = (\lambda - \lambda_0) S_0 \quad (2\text{-}11)$$

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

NOTES

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 1310 nm region.

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.

2.5.1.3.3 Fibres covered by Recommendation G.654

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

$$\tau(\lambda) = \tau_{1550} + (S_{1550}/2) (\lambda - 1550)^2 + D_{1550} \lambda \quad (2\text{-}12)$$

Here τ_{1550} is relative group delay at the wavelength $\lambda = 1550$ nm. The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated quadratic expression:

$$D(\lambda) = S_{1550} (\lambda - 1550) + D_{1550} \quad (2\text{-}13)$$

Here S_{1550} is the (uniform) dispersion-slope at 1550 nm wavelength, i.e. the value of the dispersion-slope $S_{1550}(\lambda) = dD/d\lambda$ at $\lambda = 1550$ nm. Also, D_{1550} denotes the dispersion values at $\lambda = 1550$ nm.

NOTES

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 1310 nm region.

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 S_{1550} and D_{1550}.

2.5.1.4 Presentation of the 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.

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

j) Temperature of the sample and environmental conditions (if necessary).

2.5.2 First alternative test method: The interferometric technique

2.5.2.1 General

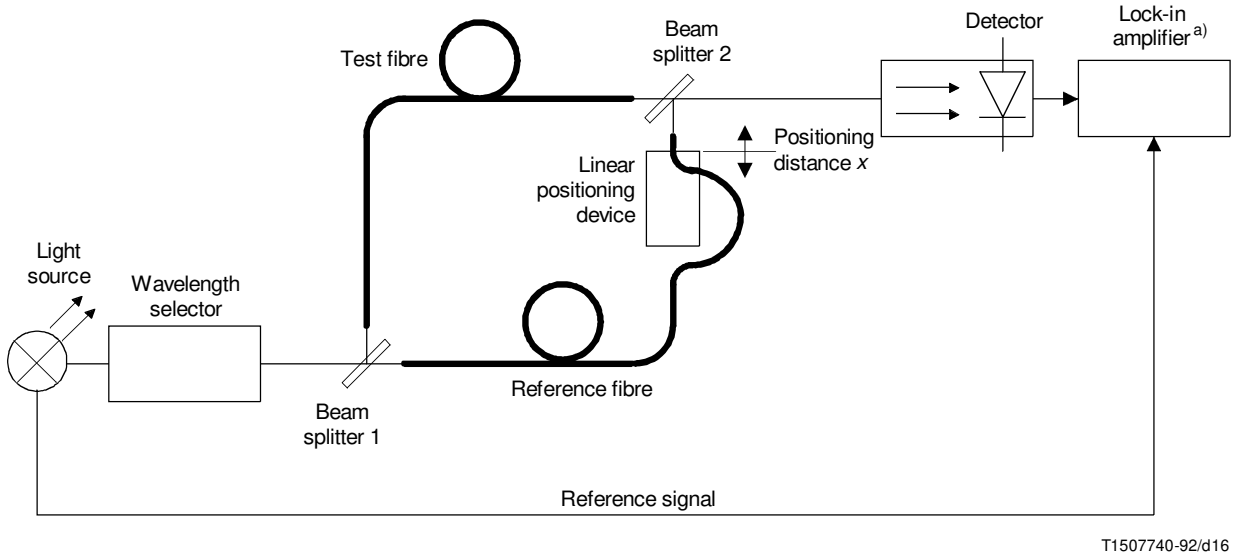
The interferometric test method allows the chromatic dispersion to be measured, using a short piece of fibre (several metres). This offers the possibility of measuring the longitudinal chromatic dispersion homogeneity of optical fibres. Moreover, it is possible to test the effect of overall or local 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 a single-mode fibre with known spectral group delay.

It should be noted that 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.

2.5.2.2 Test apparatus

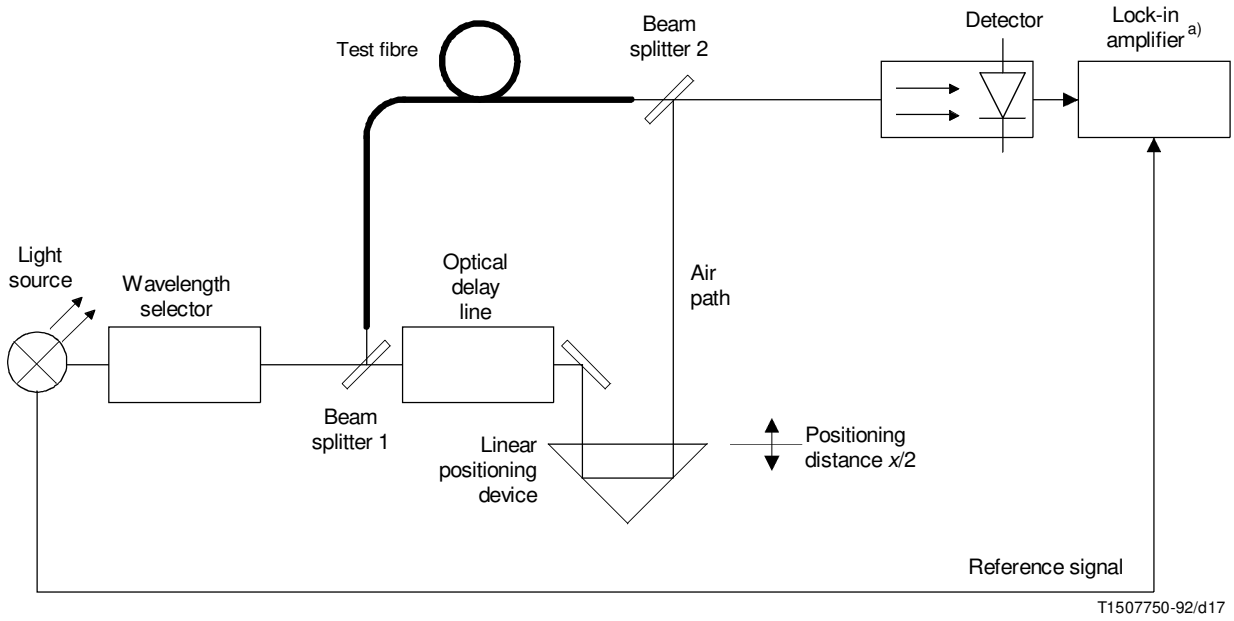
Schematic diagrams of the test apparatus using a reference fibre and an air path reference are shown in Figures 16 and 17, respectively.



a) When needed.

FIGURE 16/G.650

Schematic diagram of measurement set-up with reference fibre



a) When needed.

FIGURE 17/G.650

Schematic diagram of measurement set-up air path reference

2.5.2.2.1 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 with low-frequency modulation (50 to 500 Hz) is sufficient.

2.5.2.2.2 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.

2.5.2.2.3 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 could be upgraded, with for example a transimpedance circuit.

2.5.2.2.4 Test equipment

For the recording of the interference patterns, a lock-in amplifier may be used. Balancing of the optical length of the two paths 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.

2.5.2.2.5 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 ±1 mm. The preparation of the fibre endfaces should be carried out with reasonable care.

2.5.2.2.6 Data processing

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

2.5.2.3 Measurement procedure

1) The fibre under test is placed in the measurement set-up (Figures 16 and 17). 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 l8) determines the group delay difference $\Delta t_g(\lambda_i)$ between the reference path and the test path as follows:

$$\Delta t_g(\lambda_i) = (x_0 - x_i)/c_0 \qquad (2\text{-}14)$$

where c_0 is the velocity of light in the vacuum. The group delay of the test sample is calculated by adding the value $\Delta t_g(\lambda_i)$ 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.

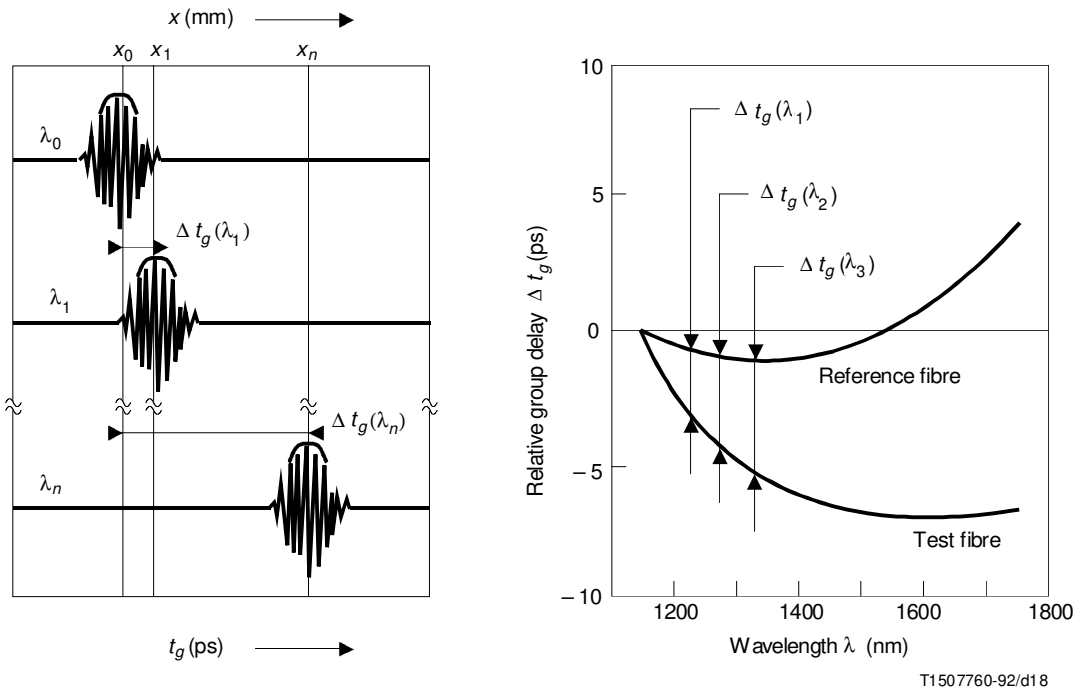


FIGURE 18/G.650

Determination of the spectral group delay

2.5.2.3.1 Fibres covered by Recommendation G.652

From the individual group delay values of the fibre under test an interpolation curve can be derived. The measured group delay per unit fibre length versus wavelength shall be fitted by the three-term Sellmeier expression (2-8).

The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated Sellmeier expression (2-9).

NOTE – Equations (2-8) and (2-9) for $\tau(\lambda)$ and $D(\lambda)$, respectively, are sufficiently accurate over the 1270-1340 nm range, but are less accurate in the 1550 nm region. Because the dispersion in the latter region is large, the reduced accuracy may be acceptable, if not, it can be improved by including data from the 1550 nm region when performing the fit. However, it should be noted that this may reduce the accuracy in the 1310 nm region.

2.5.2.3.2 Fibres covered by Recommendation G.653

The measured group delay per unit fibre length versus wavelength shall be fitted by the quadratic expression (2-10). The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated quadratic expression (2-11).

NOTE – Equations (2-10) and (2-11) for $\tau(\lambda)$ and $D(\lambda)$, respectively, are sufficiently accurate over the 1500-1600 nm range. They are not meant to be used in the 1310 nm region.

2.5.2.3.3 Fibres covered by Recommendation G.654

The measured group delay per unit fibre length versus wavelength shall be fitted by the quadratic expression (2-12). The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated quadratic expression (2-13).

NOTE – Equations (2-12) and (2-13) for $\tau(\lambda)$ and $D(\lambda)$, respectively, are sufficiently accurate over the 1500-1600 nm range. They are not meant to be used in the 1310 nm region.

2.5.2.4 Presentation of the 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) Value of the zero-dispersion wavelength and the zero-dispersion slope.

g) Fitting procedures of relative delay data with the used fitting wavelength range.

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

2.5.3 Second alternative test method: The pulse delay technique

2.5.3.1 General

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.

The group delay is measured in the time domain, by detecting, recording and processing the delay experienced by pulses at various wavelengths.

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

2.5.3.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure l5.

2.5.3.2.1 Optical source

The optical source shall be stable in position, intensity and wavelength over a time period sufficiently long to complete the measurement procedure. [Laser diodes, [laser diode array (LD-array)], wavelength tunable laser diodes (WTL) [e.g. an external cavity laser (ECL)], 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.

2.5.3.2.2 Wavelength selection

The wavelength selector and monitoring are used to select and monitor the wavelength at which the group delay is to be measured. As a wavelength selector, an optical switch, a monochromator, dispersive devices, optical filters, optical couplers, connectors 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 monitoring may be carried out by an optical fibre coupler and a wavelength meter. The wavelength selector and monitor may be used either at the input or at the output end of the fibre under test.

2.5.3.2.3 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.

2.5.3.2.4 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.

2.5.3.2.5 Delay detector

The delay detector shall measure the delay time between the reference signal and the channel signal. A high speed oscilloscope or a sampling oscilloscope could be used.

2.5.3.2.6 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.

2.5.3.3 Measurement 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 between the reference signal and the channel signal at the operating wavelength is 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.

2.5.3.3.1 Fibres covered by Recommendation G.652

The measured group delay per unit fibre length versus wavelength shall be fitted by the three-term Sellmeier expression (2-8).

The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated Sellmeier expression (2-9).

NOTE – Equations (2-8) and (2-9) for $\tau(\lambda)$ and $D(\lambda)$, respectively, are sufficiently accurate over the 1270-1340 nm range, but are less accurate in the 1550 nm region. Because the dispersion in the latter region is large, the reduced accuracy may be acceptable, if not, it can be improved by including data from the 1550 nm region when performing the fit. However, it should be noted that this may reduce the accuracy in the 1310 nm region.

2.5.3.3.2 Fibres covered by Recommendation G.653

The measured group delay per unit fibre length versus wavelength shall be fitted by the quadratic expression (2-10). The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated quadratic expression (2-11).

NOTE – Equations (2-10) and (2-11) for $\tau(\lambda)$ and $D(\lambda)$, respectively, are sufficiently accurate over the 1500-1600 nm range. They are not meant to be used in the 1310 nm region.

2.5.3.3.3 Fibres covered by Recommendation G.654

The measured group delay per unit fibre length versus wavelength shall be fitted by the quadratic expression (2-12). The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated quadratic expression (2-13).

NOTE – Equations (2-12) and (2-13) for $\tau(\lambda)$ and $D(\lambda)$, respectively, are sufficiently accurate over the 1500-1600 nm range. They are not meant to be used in the 1310 nm region.

2.5.3.4 Presentation of the 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.

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

j) Temperature of the sample and environmental conditions (if necessary).

2.6 Test methods for prooftesting

2.6.1 Reference test method: Longitudinal tension

2.6.1.1 General

a) This test method describes procedures for briefly applying tensile loads to an entire continuous length of fibre. The initial length may break into several shorter lengths, and each shorter length is considered to have passed the prooftest.

b) Standard ambient environmental conditions are used for storage and prooftesting: $23 \pm 5°$ C and $50 \pm 20\%$ relative humidity. The storage time prior to prooftesting is an item for further study.

c) Either stress σ or strain ε may be used in the measurement. They are related by:

$$\sigma = E(1 + c\varepsilon)\varepsilon \qquad (2\text{-}15)$$

where E is Young's modulus at zero stress, and c is a parameter (typically between 3 and 6). The determination of parameters E and c, if needed, is an item for further study.

d) The stress σ is calculated from the tension *T* as:

$$\sigma = \frac{T}{\pi a^2} \tag{2-16}$$

where 2a is the diameter of the glass fibre (125 μm). The effects of fibre cross-sectional non-uniformity and the contribution of fibre coatings and/or buffers are items for further study.

2.6.1.1.1 Prooftest parameters

a) The behaviour of stress versus time is indicated schematically in Figure 19. Here σ_p is the specified proofstress during the specified dwell-time t_d, while t_ℓ and t_u are the load and unload times, respectively.

b) If an alternate value t_a of dwell-time is used, an alternate value

$$\sigma_a = \sigma_p \left[\frac{t_d}{t_a} \right]^{\frac{1}{n_d}} \tag{2-17}$$

of proofstress may be used. The value of the dynamic fatigue parameter n_d is determined by a dynamic fatigue test method. The static fatigue parameter, n_s, could be used alternatively, if n_d is not known. If neither parameter is known, a value of 20 for this calculation can be assumed.

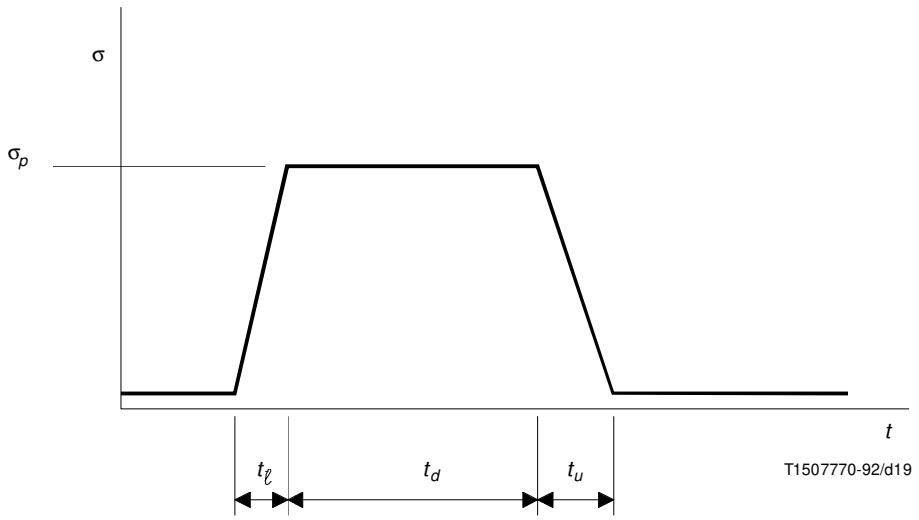


FIGURE 19/G.650

Stress s vs. time *t* during prooftesting

2.6.1.2 Test apparatus

2.6.1.2.1 Operating procedure requirements

a) In the pay-out region, the fibre is maintained with a low value of stress typically not exceeding 10% of the proofstress.

b) In the load region, fibre stress ramps up from the low value in the pay-out region to the full proofstress in the prooftest region. The load-time is t_ℓ.

c) In the prooftest region, the proofstress σ_p is applied uniformly along the fibre length for a dwell-time t_d. A gauge may monitor tension, which must not decrease more than 5% from its mean value. The dwell-time can be adjusted according to the fibre length within the prooftest region and the speed of the fibre through the region.

d) In the unload region, fibre stress ramps down from the full value in the prooftest region to a low value in the take-up region. The unload-time is t_u.

e) Ramping up and ramping down shall be accomplished as linearly as possible, and the latter as rapidly as possible.

f) In the take-up region, the fibre is maintained with a low value of stress typically not exceeding 10% of the proofstress.

g) The tension during passage around any mandrels or capstans in the take-up region typically shall not exceed 10% of the proofstress.

2.6.1.2.2 Prooftest machines

a) *Braked-capstan machine* (Figure 20)

Guide pulleys guide the fibre onto the first capstan drum and off the last capstan drum. A friction coating on the capstans is used to prevent slippage, but without damage to the fibre coatings. The top and bottom drums of each capstan pair are mechanically synchronized. The top capstans are canted slightly so the fibre does not rub against itself as it returns to the bottom drum.

The proofstress is applied by driving the second pair of capstans by a constant-speed motor, while uniformly braking the first air of capstans.

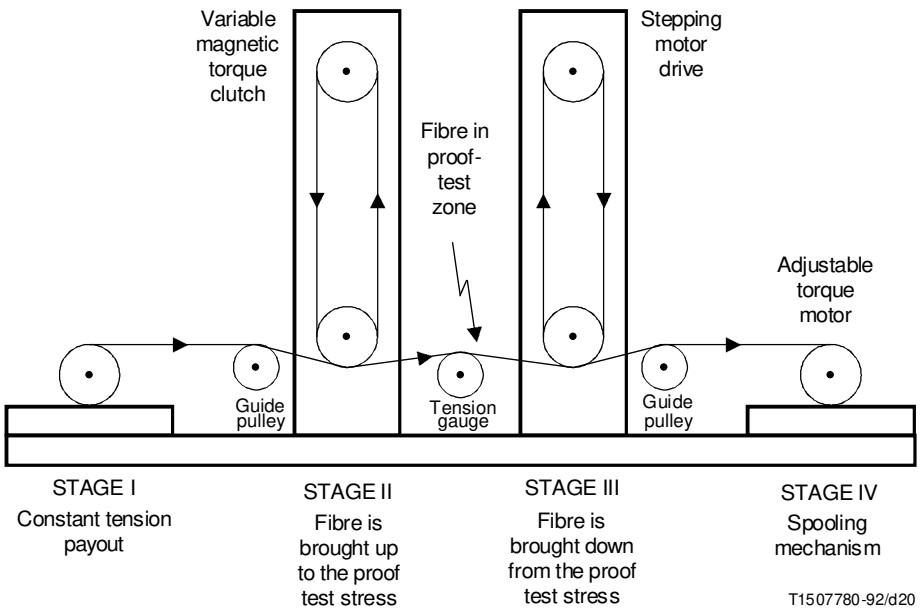


FIGURE 20/G.650

Typical arrangement of a braked-capstan prooftest machine

b) *Dead-weight machine* (Figure 21)

The pay-out dancer and the take-up dancer pulley are light enough to guide the fibre with minimal tension. The pay-out capstan and the take-up capstan are synchronized with each other. The capstan pinch belts prevent slippage at the capstans, but without additional stress to the fibre or damage to the fibre coatings.

A load-arm and a dead-weight on a plate are attached to the shaft of a dead-weight dancer pulley to provide the proofstress to the fibre. An optional idler pulley provides an increased fibre gauge length if needed.

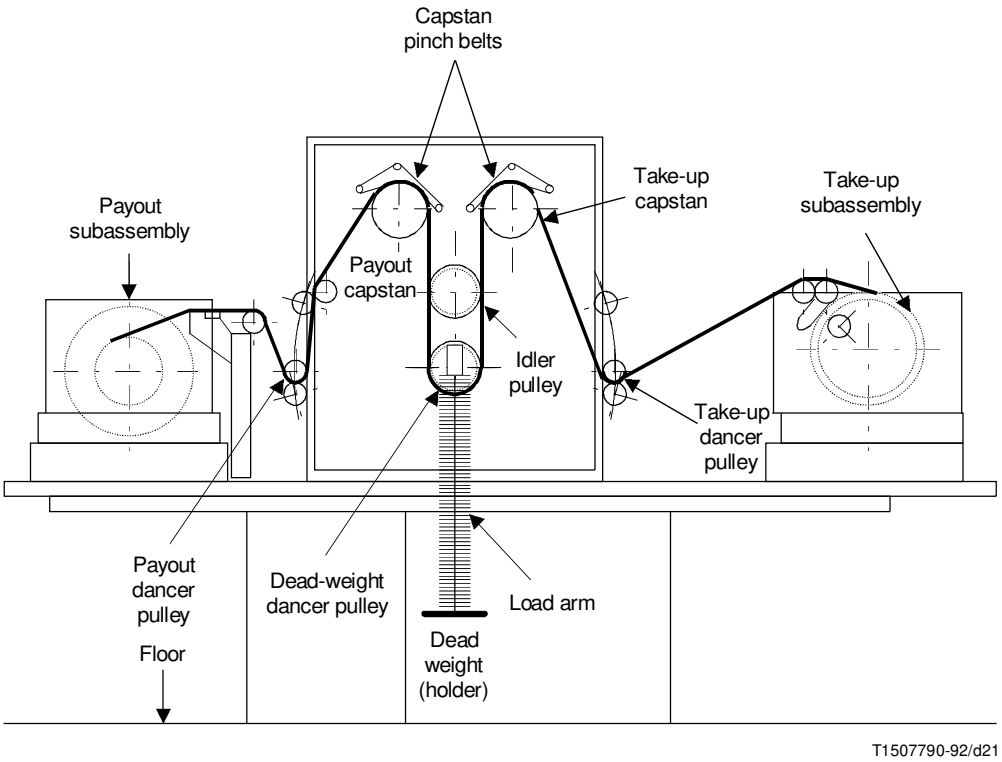


FIGURE 21/G.650

Typical arrangement of a dead-weight prooftest machine

2.6.1.3 Measurement procedure

2.6.1.3.1 Sample

a) The test sample shall consist of the entire length of optical fibre, minus a maximum of 10 m at each end. Those ends may not necessarily be subjected to the full prooftension, and must be discarded.

b) Fibre failure after prooftesting shall be evidenced by complete breakage or by gross stretching of the coating in the failure area. Examination methods include an OTDR and perhaps visual inspection. After broken or damaged areas are removed, the surviving fibre lengths are considered to have passed the prooftest procedure.

2.6.1.3.2 Calculation

lf the machine is calibrated in tension, the stress is calculated from equation (2-16). Strain may be obtained from equation (2-15).

2.6.1.4 Presentation of the results

The following details shall be presented:

a) General description of the apparatus.

b) Fibre identification.

c) If different from the specified values, the alternative proofstress (or proofstrain) and the alternative dwell-time used, along with the value of the dynamic stress corrosion coefficient assumed.