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SERIES G: TRANSMISSION SYSTEMS AND MEDIA,
DIGITAL SYSTEMS AND NETWORKS

Transmission media characteristics – Optical fibre cables

**Definition and test methods for the relevant
parameters of single-mode fibres**

ITU-T Recommendation G.650

(Previously CCITT Recommendation)

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ITU-T RECOMMENDATION G.650

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

Source

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Recommendation G.650

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

(revised in 1997)

1 Definition of the relevant parameters for single-mode fibres

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 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 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 proof test level

The proof test 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 of the LP₀₁ mode giving rise to a spatial intensity distribution in the fibre.

1.3.2 mode field diameter

The Mode Field Diameter (MFD) $2w$ represents a measure of the transverse extent of the electromagnetic field intensity of the mode in a fibre cross-section and it is defined from the far-field intensity distribution $F^2(\theta)$, θ being the far-field angle, through the following equation:

$$2w = \frac{\lambda}{\pi} \left[\frac{2 \int_0^{\frac{\pi}{2}} F^2(\theta) \sin \theta \cos \theta d\theta}{\int_0^{\frac{\pi}{2}} F^2(\theta) \sin^3 \theta \cos \theta d\theta} \right]^{1/2} \quad (1-1)$$

1.3.3 mode field centre

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

NOTE 1 – The centroid is located at r_c and is the normalized intensity-weighted integral of the position vector r .

$$r_c = \frac{\iint_{Area} rI(r)dA}{\iint_{Area} I(r)dA} \quad (1-2)$$

NOTE 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 of Recommendations 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 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

Change of the delay of a light pulse for a unit fibre length caused by a unit wavelength change. It is usually expressed in ps/(nm · km).

NOTE – The duration of a light pulse per unit source spectrum width after having traversed a unit length of fibre is equal to the chromatic dispersion coefficient, if the following prerequisites are given:

- 1) the source has a wide spectrum;
- 2) the duration of the pulse at the fibre input is short as compared to that at the output, the wavelength is different from the zero-dispersion wavelength.

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

Theoretical cut-off wavelength is the shortest wavelength at which a single mode can propagate in a single-mode fibre. This parameter can be computed from the refractive index profile of the fibre. At wavelengths below the theoretical cut-off wavelength, several modes propagate and the fibre is no longer single-mode but multimode.

In optical fibres, the change from multimode to single-mode behaviour does not occur at an isolated wavelength, but rather smoothly over a range of wavelengths. Consequently, for determining fibre performance in a telecommunications network, theoretical cut-off wavelength is less useful than the actual threshold wavelength for single-mode performance when the fibre is in operation. Thus a more effective parameter called cut-off wavelength shall be introduced for single-mode fibre specifications as defined in the following:

Cut-off wavelength is defined as 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 0.1 dB. According to this definition, the second order (LP₁₁) mode undergoes 19.3 dB more attenuation than the fundamental (LP₀₁) mode when the modes are equally excited.

Because cut-off wavelength depends on the length and bends of the fibre, as well as its strain condition, the resulting value of cut-off wavelength depends on whether the measured fibre is configured in a deployed cabled condition, or whether the fibre is short and uncabled. Consequently, there are three types of cut-off wavelength defined: **cable cut-off wavelength**, **fibre cut-off wavelength** and **jumper cable cut-off wavelength**.

cable cut-off wavelength λ_{cc} – Cable cut-off wavelength is measured prior to installation on a substantially straight 22 m cable length prepared by exposing 1 m of primary-coated fibre at either end, the exposed ends each incorporating a 40 mm radius loop. Alternatively, this parameter may be measured on 22 m of primary-coated uncabled fibre loosely constrained in loops > 140 mm radius, incorporating a 40 mm radius loop at either end.

Alternative configurations may be used if the empirical results are demonstrated to be either equivalent within 10 nm, or they are greater than those achieved with the sample configurations. For example, two 40 mm radius loops in a two-metre length of uncabled fibre meets this equivalent criterion for some fibre and cable designs.

fibre cut-off wavelength λ_c – Fibre cut-off wavelength is measured on uncabled primary-coated fibre in the following configuration: 2 metres, with one loop of 140 mm radius (or an equivalent, e.g. split mandrel) loosely constrained with the rest of the fibre kept essentially straight.

jumper cable cut-off wavelength λ_{cj} – Jumper cable cut-off wavelength is measured on jumper cables in the following configuration: 2 metres, with one loop of x mm radius¹ (or an equivalent, e.g. split mandrel), with the rest of the jumper cable kept essentially straight.

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 :

$$\lambda_{cc} < \lambda_s \quad (1-3)$$

This ensures that each individual cable section is sufficiently single mode. Any joint that is not perfect will create some higher order (LP₁₁) 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 LP₁₁ mode before it reaches the next joint. If inequality (1-3) is satisfied in the shortest cable section, it will be automatically satisfied in all longer cable sections, and single-mode system operation will occur regardless of the elementary section length.

Fibre cut-off wavelength and mode field diameter can be combined to estimate a fibre's bend sensitivity. High fibre cut-off and a small mode field diameter result in a more bend resistant fibre. This explains why it is often desirable to specify higher values of cut-off wavelength λ_c , even if the upper limit of this parameter exceeds the operating wavelength. All practical installation techniques and cable designs will ensure a cable cut-off wavelength below the operating wavelength.

Since specification of cable cut-off wavelength, λ_{cc} , is a more direct way of ensuring single-mode cable operation, specifying this is preferred to specifying fibre cut-off wavelength, λ_c . However, when circumstances do not readily permit the specification of λ_{cc} (e.g. in single-fibre cable such as pigtailed, jumpers or cables to be deployed in a significantly different manner than in the λ_{cc} RTM), then specifying an upper limit for λ_{cj} or λ_c is appropriate. This option is addressed in Recommendations G.652, G.653, G.654 and G.655.

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:

$$A(\lambda) = 10 \log \frac{P_1(\lambda)}{P_2(\lambda)} \quad (\text{dB}) \quad (1-4)$$

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:

$$a(\lambda) = \frac{A(\lambda)}{L} \quad (\text{dB/ unit length}) \quad (1-5)$$

¹ x is specified as 76 mm by some Administrations.

1.6.3 Polarization Mode Dispersion (PMD)

1.6.3.1 the phenomenon of PMD

Polarization mode dispersion is the Differential Group Delay time (DGD) between two orthogonally polarized modes, which causes pulse spreading in digital systems and distortions in analogue systems.

NOTE 1 – In ideal circular symmetric fibres, the two polarization modes propagate with the same velocity. However, real fibres cannot be perfectly circular and can undergo local stresses; consequently, the propagating light is split into two local polarization modes travelling at different velocities. These asymmetry characteristics vary randomly along the fibre and in time, leading to a statistical behaviour of PMD. A "maximum" value of DGD can be inferred from the statistics.

NOTE 2 – For a given arbitrarily deployed fibre at a given time and optical frequency, there always exist two polarization states, called Principal States of Polarization (PSP, see 1.6.3.2) such that the pulse spreading due to PMD vanishes, if only one PSP is excited. On the contrary, the maximum pulse spread due to PMD occurs when both PSPs are equally excited, and is related to the difference in the group delays associated with the two PSPs.

1.6.3.2 principal States of Polarization (PSP)

When operating an optical fibre at a wavelength longer than the cut-off wavelength in a quasi-monochromatic regime, the output PSPs are the two orthogonal output states of polarization for which the output polarizations do not vary when the optical frequency is varied slightly. The corresponding orthogonal input polarization states are the input PSPs.

NOTE 1 – The local birefringence changes along the fibre, and the PSP depends on the fibre length (contrary to hi-bi fibres).

NOTE 2 – The PSPs are random complex vectors depending on time and optical frequency. However, according to the definition, there exists a small frequency range, the PSP bandwidth, over which they can be considered practically constant.

NOTE 3 – If a signal has a bandwidth broader than the PSPs bandwidth, second order PMD effects come into play. They may imply a depolarization of the output field, together with an additional chromatic dispersion effect.

1.6.3.3 differential group delay ($[\delta\tau(\nu)] = \text{ps}$)

The Differential Group Delay (DGD) is the time difference in the group delays of the PSPs.

NOTE – The DGD between two modes is wavelength dependent and can vary in time due to environmental conditions. Variations by one order of magnitude are typical. The statistical distribution of the differential group delays is determined by the mean polarization mode coupling length, h , the average modal birefringence and the degree of coherence of the source. For a standard optical fibre cable of length L , such that $L \gg h$, as is mostly the case in practice, strong mode coupling occurs between the polarization modes. In such a case, the probability distribution of the DGDs is a Maxwellian distribution.

1.6.3.4 PMD delay

The equivalence of the following three PMD delay definitions is believed to be within the reproducibility of the measurement for all practical cases.

The second moment PMD delay P_s is defined as twice the root mean square deviation (2σ) of the time dependent light intensity distribution $I(t)$ at the output of the fibre, deprived of the chromatic dispersion contribution, when a short pulse is launched into the fibre, that is:

$$P_s = 2 \left(\langle t^2 \rangle - \langle t \rangle^2 \right)^{1/2} = 2 \left(\frac{\int I(t)t^2 dt}{\int I(t)dt} - \left(\frac{\int I(t)t dt}{\int I(t)dt} \right)^2 \right)^{1/2} \quad (1-6)$$

t represents the arrival time at the output of the fibre.

NOTE 1 – In practical cases, the width of the launched pulse and the broadening due to chromatic dispersion must be deconvolved to obtain P_s . For details, see the interferometric test method for PMD, in 2.7.3.

The mean differential group delay P_m is the differential group delay $\delta\tau(\nu)$ between the principal states of polarization, averaged over the optical frequency range (ν_1, ν_2):

$$P_m = \frac{\int_{\nu_1}^{\nu_2} \delta\tau(\nu) c \nu}{\nu_2 - \nu_1} \quad (1-7)$$

NOTE 2 – Averaging over temperature, time or mechanical perturbations is generally an acceptable alternative to averaging over frequency.

The r.m.s. differential group delay P_r is defined as:

$$P_r = \left(\frac{\int_{\nu_1}^{\nu_2} \delta\tau(\nu)^2 d\nu}{\nu_2 - \nu_1} \right)^{1/2} \quad (1-8)$$

1.6.3.5 PMD coefficient

Two cases shall be distinguished:

- Weak mode coupling (short fibres):

$$PMD_c [ps / km] = P_s / L, P_m / L, \text{ or } P_r / L \quad (1-9)$$

- Strong mode coupling (long fibres):

$$PMD_c [ps / \sqrt{km}] = P_s / \sqrt{L}, P_m / \sqrt{L}, \text{ or } P_r / \sqrt{L} \quad (1-10)$$

NOTE – Strong mode coupling is mostly observed in installed cables typically longer than 2 km. Under normal conditions, the differential group delays are random functions of optical wavelength, of time, and vary at random from one fibre to the other. Therefore, in most cases, the PMD coefficient has to be calculated using the square root formula 1-10.

High birefringent fibres do not show a statistical distribution of the differential group delays because there is almost no or very weak mode coupling. Typically, the differential group delays are constant.

However, in a few cases, intermediate coupling can be observed on installed cables. An exact classification is under study.

To estimate the impact on system performance, it has to be started whether the differential group delays are constant or statistically distributed.

Instantaneous values of the differential group delays limit the transmission capacity of digital systems. The derivative of the differential group delay with respect to the wavelength limits the signal-to-noise ratio in analogue systems. Therefore, the statistical distribution of the differential

group delays (vs. time and/or vs. wavelength) plays an important role in predicting real system performance.

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 $F^2(\theta)$ according to the definition given in 1.3.2. The integration limits are shown to be 0 and $\pi/2$, but it is understood that this notation implies the truncation of the integrals in the limit of increasing argument. While the maximum physical value of the argument θ is $\pi/2$, the integrands rapidly approach zero before this value is reached. The relative error in the determination of the mode field diameter, introduced by this truncation, is discussed in 2.1.1.2.6.

2.1.1.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure 1.

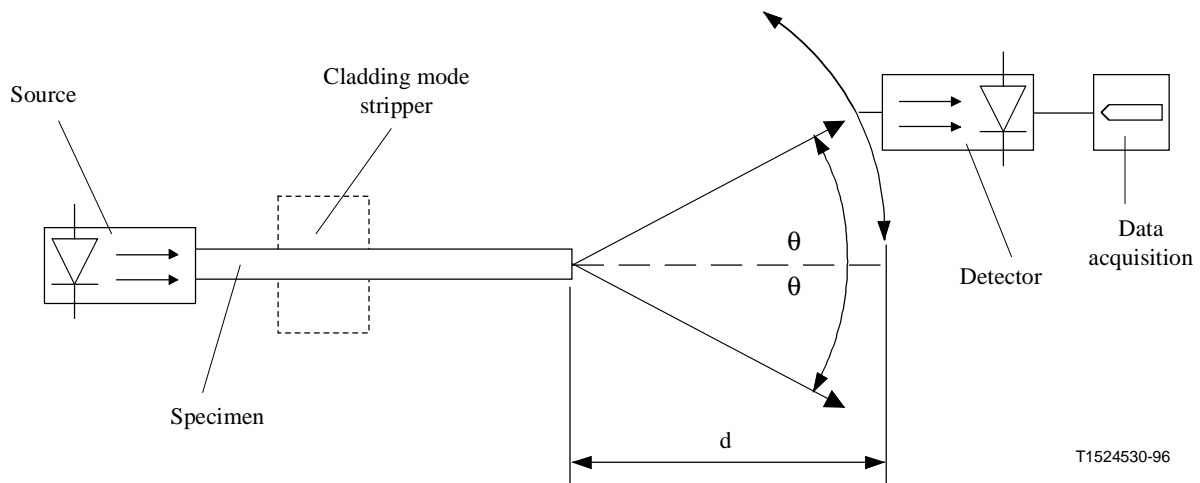


Figure 1/G.650 – Typical arrangement of the far-field scan set-up

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. The FWHM spectral width shall be no greater than 10 nm.

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 (LP₀₁) 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 $40wb/\lambda$, 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 Recommendations G.652 and G.653, respectively.

NOTE 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%.

NOTE 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 no greater than 0.5° , the far-field intensity distribution, $F^2(\theta)$, is measured, and the mode field diameter is calculated from equation 1-1.

2.1.1.4 Presentation of the results

- 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 aperture transmission function $a(x)$, ($x = D \cdot \tan \theta$ being the aperture radius, and D the distance between the aperture and the fibre):

$$2w = (\lambda / \pi D) \left[\int_0^\infty a(x) \frac{x}{(x^2 + D^2)^2} dx \right]^{-1/2} \quad (2-1)$$

The mathematical equivalence of equations 1-1 and 2-1 is valid in the approximation of small angles θ . Under this approximation, equation 2-1 can be derived from equation 1-1 by integration.

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, $a(x)$, is found as:

$$a(x) = 1 - \frac{P(x)}{P_{\max}} \quad (2-2)$$

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

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 near-field scan

2.1.3.1 General

The mode field diameter is determined from the near-field intensity distribution $f^2(r)$: (r being the radial coordinate):

$$2w = 2 \left[\frac{\int_0^{\infty} r f^2(r) dr}{\int_0^{\infty} r \left[\frac{df(r)}{dr} \right]^2 dr} \right]^{\frac{1}{2}} \quad (2-3)$$

The mathematical equivalence of equations 1-1 and 2-3 is valid in the approximation of small angles θ . Under this approximation, the near-field $f(r)$ and the far-field $F(\theta)$ from a Hankel pair. By means of the Hankel transform, it is possible to pass from equation 1-1 to equation 2-3 and reverse.

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

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.

2.1.3.2.7 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 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 equation 2-3. 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 $F^2(\theta)$ may be used to compute the mode field diameter from equation 1-1.

NOTE – Discriminate between the radial coordinate r in the fibre end face and the radial coordinate Mr of the scanning detector in the image plane, where M is the magnification.

2.1.3.4 Presentation of the results

- 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.

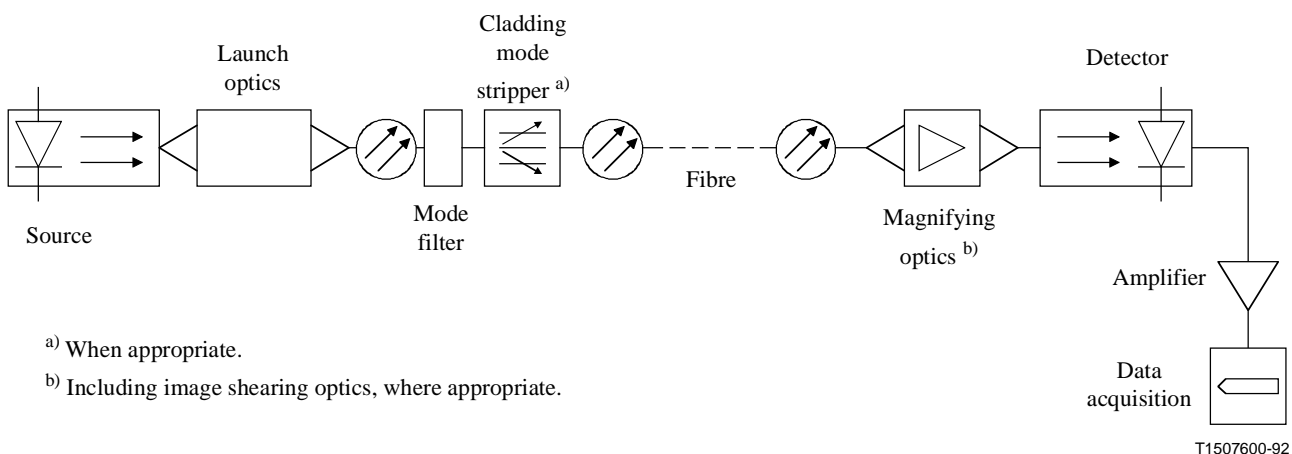


Figure 2/G.650 – Typical arrangement of the transmitted near-field set-up

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 defocusing 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, focusing 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 focused image(s) of the output end of the fibre shall be scanned by the detector, according to the specification requirements. The focusing shall be performed with maximum accuracy, in order to reduce dimensional errors due to the scanning of a defocused 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

- 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 refracted 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 focused 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 focused spot of light. This depends both on the numerical aperture of the focusing 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.

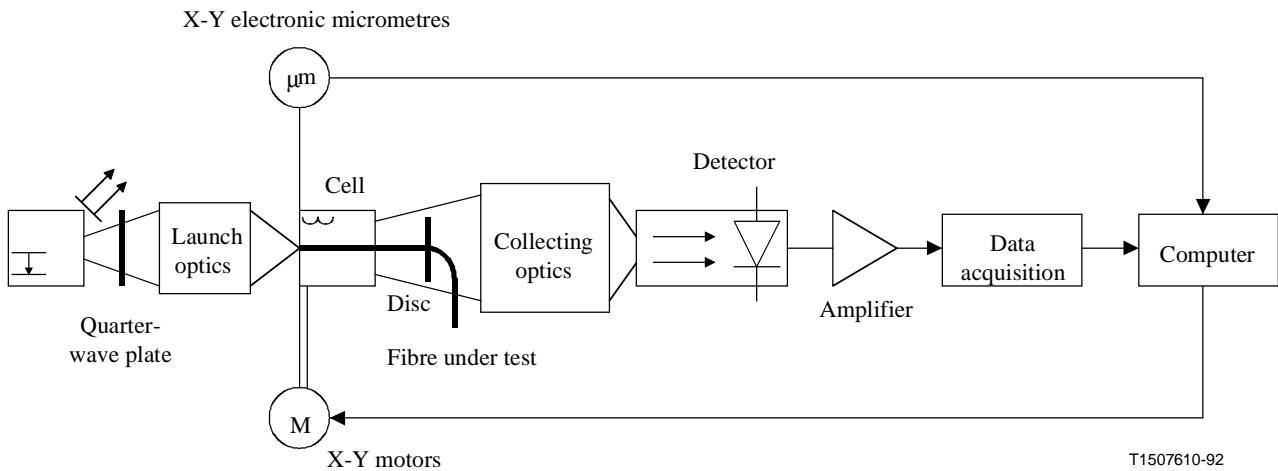


Figure 3/G.650 – Typical arrangement of the refracted near-field test set-up

2.2.2.2.1 Source

A stable laser giving about 1 mW of power in the TEM₀₀ 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.

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 focused 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 focused 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 micrometres.

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 less than 2 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. Under 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 focused on the fibre end face.

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

The focused 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 clause 1 will be performed starting from the core and cladding contours data. An index profile measurement actually yields the core concentricity error, but this generally is a good approximation of the mode-field concentricity error.

2.2.2.4 Presentation of the results

- 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 sample 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. The side-view technique actually measures the core concentricity error but this generally is a good approximation of the MFCE.

2.2.3.2 Test apparatus

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

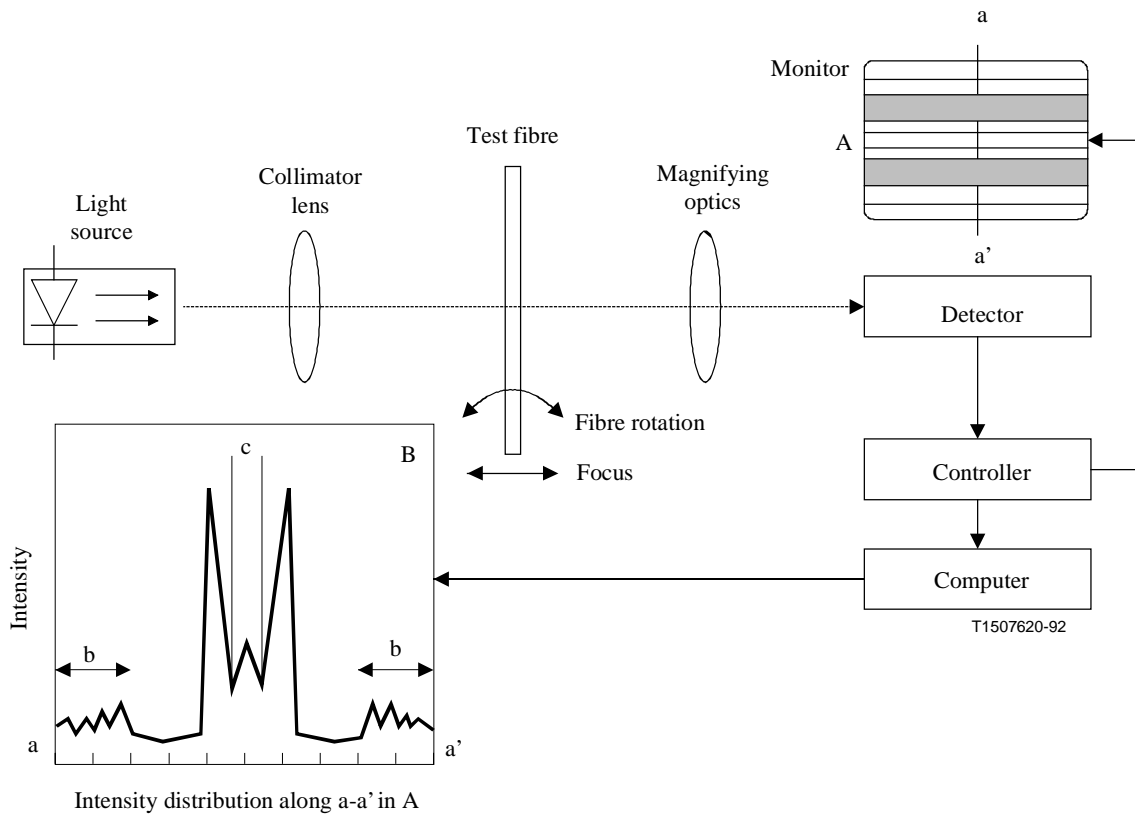


Figure 4/G.650 – Schematic diagram of side-view measurement system

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 radial intensity distribution in the magnified image (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.

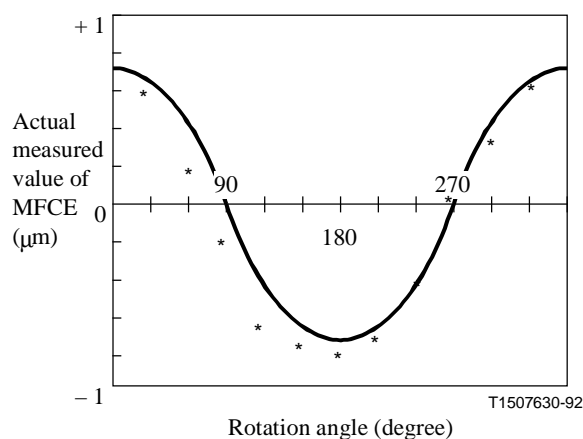


Figure 5/G.650 – Measured value of the MFCE as a function of rotation angle

2.2.3.4 Presentation of the results

- a) Test arrangement.
- b) Fibre identification.
- c) Spectral characteristics of the source.
- d) Indication of repeatability and accuracy.
- e) Plot of nominal MFCE versus rotation angle.
- f) MFCE, cladding diameter and cladding non-circularity.
- g) Temperature of the sample and environmental conditions (if necessary).

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

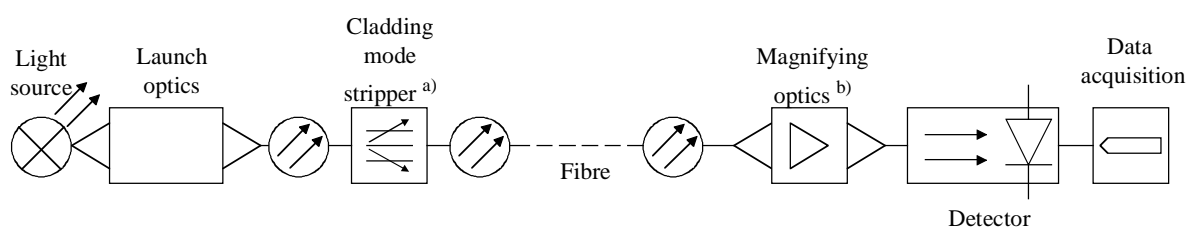
2.2.4.1 General

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 appropriate.

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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 defocusing 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 be 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 focused image(s) of the output end of the fibre shall be examined according to the specification requirements. Defocusing errors should be minimized to reduce dimensional errors in the measurement. The desired geometrical parameters are then calculated.

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 and reference test method for the cut-off wavelength (λ_{cj}) of jumper cables: 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 LP₀₁ and LP₁₁ 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 LP₁₁ 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 LP₁₁ 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 spectral attenuation of the test specimen, relative to the reference power is:

$$a(\lambda) = 10 \log \frac{P_1(\lambda)}{P_c(\lambda)} \quad (2-4)$$

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

Assuming a straight line representation of the upper wavelength region, the deviation of higher-order modes from the fundamental mode is:

$$\Delta a(\lambda) = a(\lambda) - (A_u + B_u \lambda) \quad (2-5)$$

A_u and B_u are determined so that $(A_u + B_u \lambda)$ represents the portion of the spectral attenuation curve at wavelengths above the region where the attenuation of higher order modes is accelerated (transition region). For method a), both A_u and B_u may be set to zero. See Figures 7a and 8a.

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. $a(\lambda)$ is equal to the logarithmic ratio between the total power emerging from the sample, including the LP₁₁ mode power, and the fundamental mode power. When the modes are uniformly excited in accordance with 2.3.1.2.3, $a(\lambda)$ then also yields the LP₁₁ mode attenuation $A(\lambda)$ in dB in the test sample:

$$A(\lambda) = 10 \log \left[\left(\frac{P_1(\lambda)}{P_2(\lambda)} - 1 \right) / 2 \right] \quad (2-6)$$

2.3.1.3.4 Determination of cut-off wavelength

In the transition region, higher-order mode power is reduced with increasing wavelength. Fibre cut-off wavelength, λ_c , is defined as the wavelength at which the higher-order mode power relative to the fundamental mode power, $\Delta a(\lambda)$, has been reduced to 0.1 dB.

Figures 7b and 8b illustrate "humps" that sometimes appear near the cut-off wavelength. In the absence of humps (see Figures 7a and 8a), accurate determination of λ_c can be achieved without algorithms. Optionally, for precision improvement, fitting algorithms based on the following equations can be used when humps are present. Appendix I contains examples of such algorithms.

$$\gamma(\lambda) = 10 \log \left[- \frac{10}{A} \log \left(\frac{10^{\Delta a(\lambda)/10} - 1}{\rho} \right) \right] \quad (2-7)$$

$$A = 10 \log \left[\rho / (10^{0.01} - 1) \right] \quad (2-8)$$

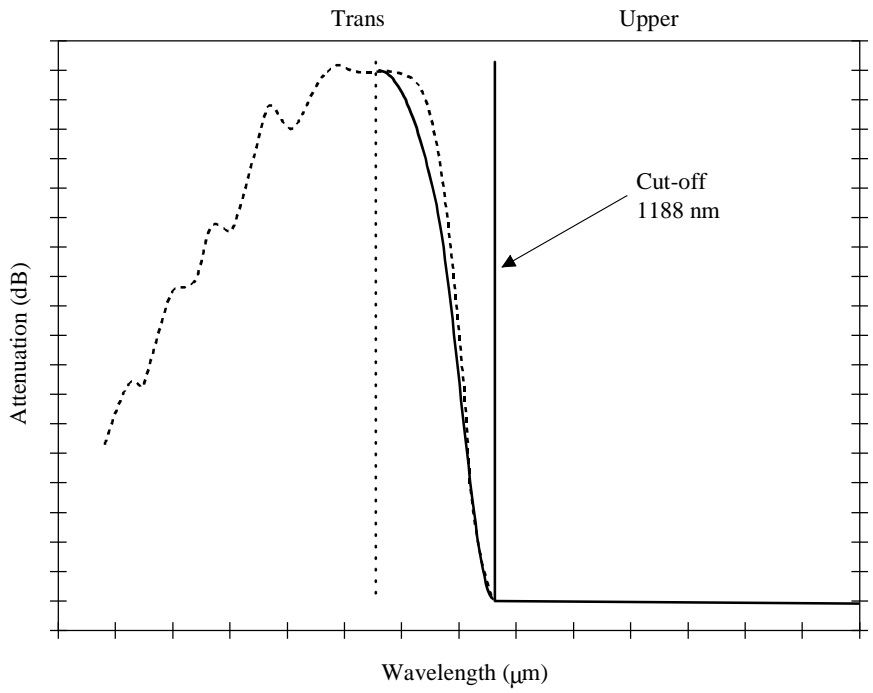
Unless otherwise specified, $\rho = 2$. (2-9)

When the coefficients of:

$$A_t + B_t \lambda = -Y(\lambda) \quad (2-10)$$

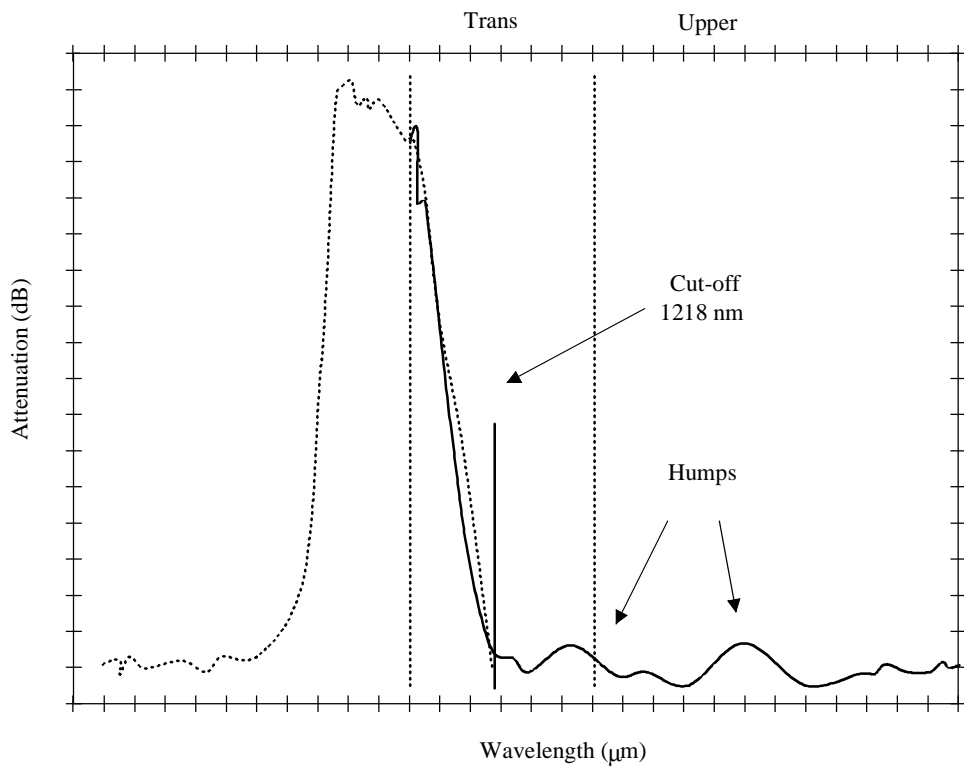
are determined for wavelengths in the transition region, then:

$$\lambda_c = - \frac{A_t}{B_t} \quad (2-11)$$



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Figure 7a/G.650 – Single-mode reference cut-off plot



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Figure 7b/G.650 – Single-mode reference cut-off plot with humps

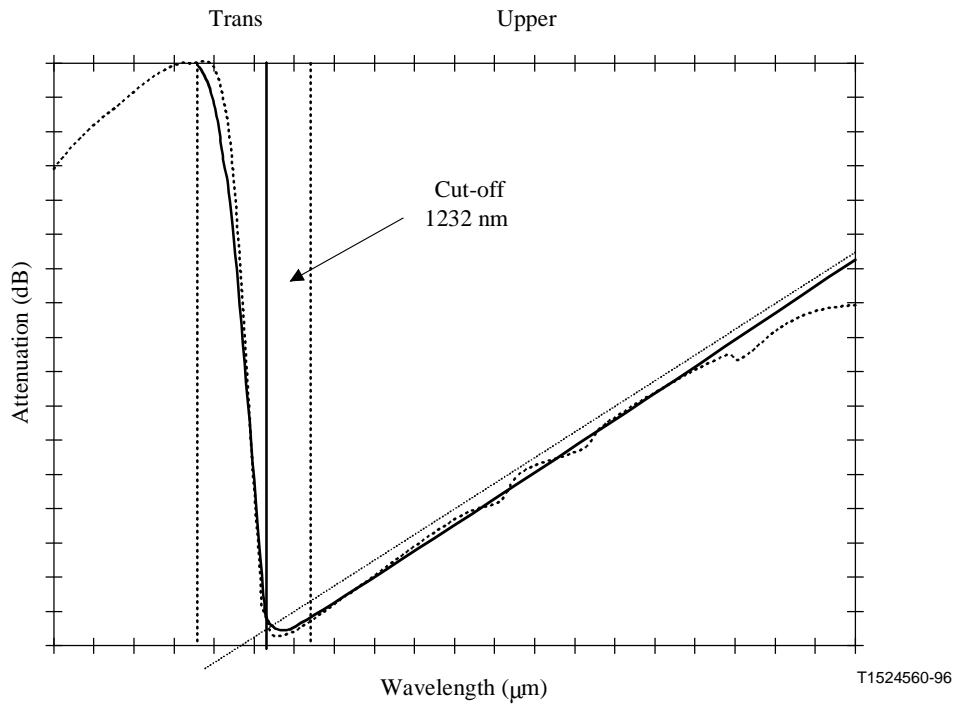


Figure 8a/G.650 – Multimode reference cut-off plot

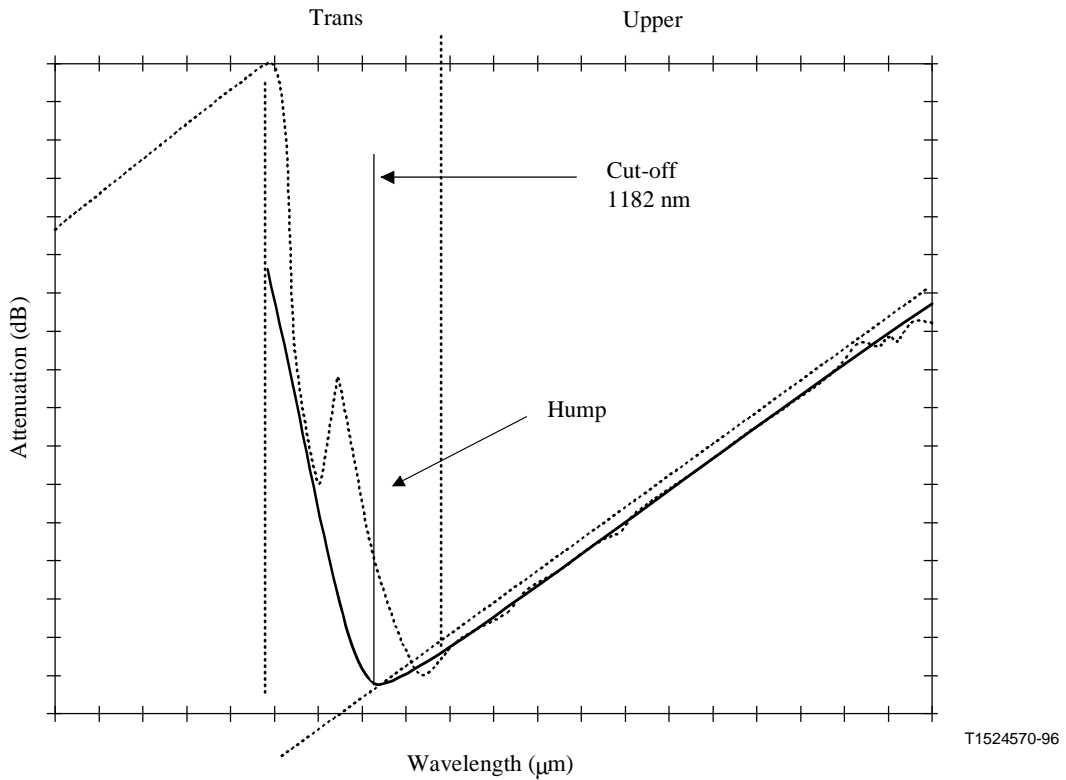


Figure 8b/G.650 – Multimode reference cut-off plot with hump

NOTE – According to the definition, the LP₁₁ mode attenuation in the test sample is 19.3 dB at the cut-off wavelength.

2.3.1.4 Jumper cable cut-off wavelength

Jumper cable cut-off wavelength is measured using the apparatus, procedures, and calculations of cut-off wavelength, with the following exceptions:

- 1) The jumper cable is measured with secondary coatings that are used in the applications.
- 2) The bend radius is specified as X mm.

NOTE – X is specified as 76 mm by some Administrations.

2.3.1.5 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 $a(\lambda)$ (if required).
- i) Measurement type, i.e. cut-off wavelength or jumper cable cut-off wavelength.
- j) Bend radius (for jumper cable cut-off wavelength only).
- k) Interpolation method (if used).

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.

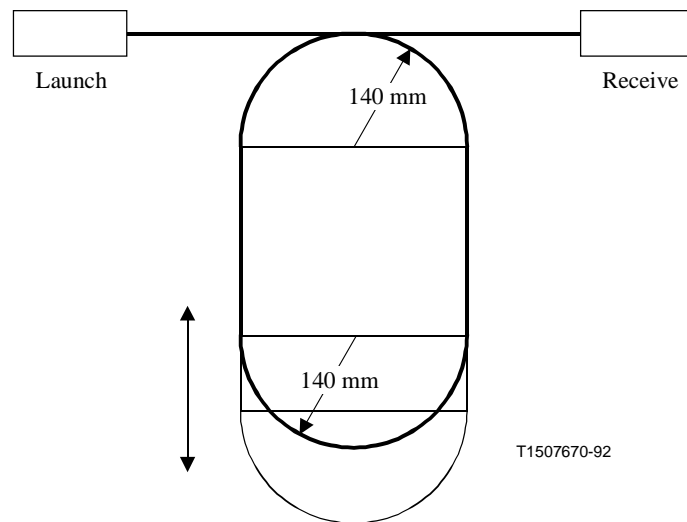


Figure 9/G.650 – Fibre deployment: Cut-off wavelength by the split-mandrel technique

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 2.3.1.5)

2.3.3 Reference test method for the cut-off wavelength (λ_{cc}) of the cabled fibre: 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.

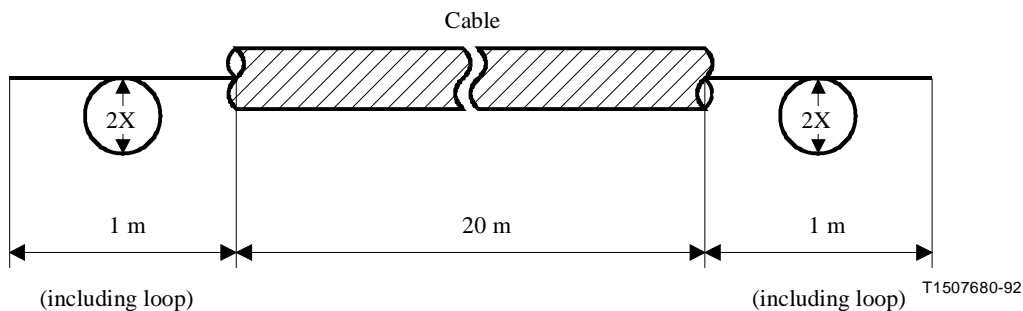


Figure 10/G.650 – Deployment condition for measurement of the cabled fibre cut-off wavelength

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

$$R(\lambda) = 10 \log \frac{P_1(\lambda)}{P_i(\lambda)} \quad (2-11 \text{ bis})$$

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

2.3.3.3.4 Determination of cabled fibre cut-off wavelength

The calculations and method of determining cable cut-off wavelength, λ_{cc} , are the same as for fibre cut-off wavelength. See 2.3.1.3.3 and 2.3.1.3.4.

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, and plot of $R(\lambda)$ (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.

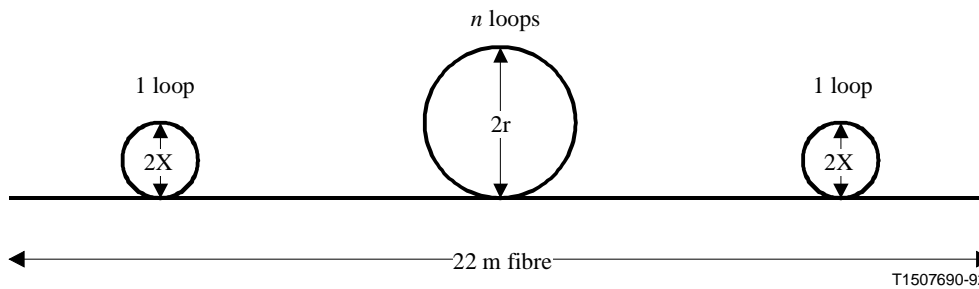


Figure 11/G.650 – Deployment condition for measurement of λ_{cc} on uncabled fibres

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).

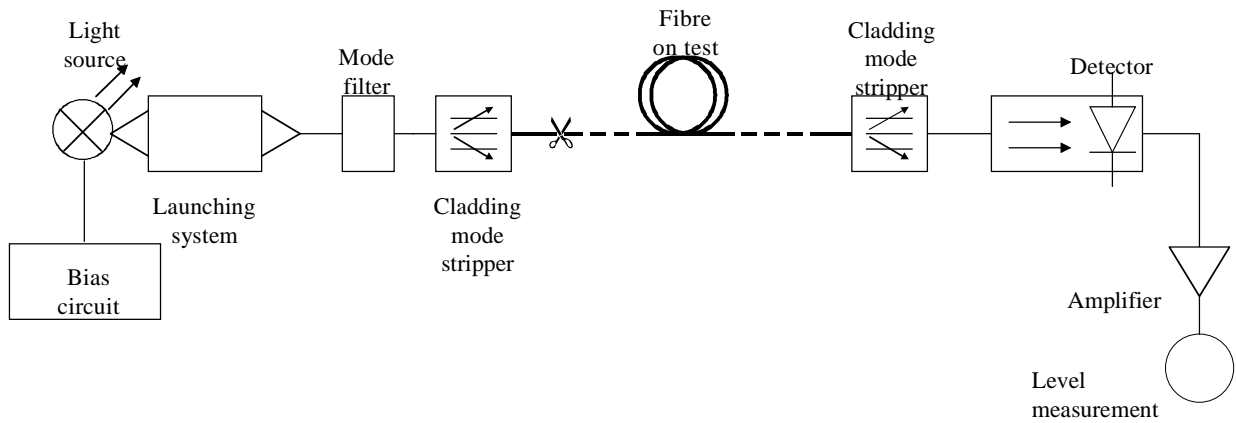
2.4.1 Reference test method: The cut-back technique

2.4.1.1 General

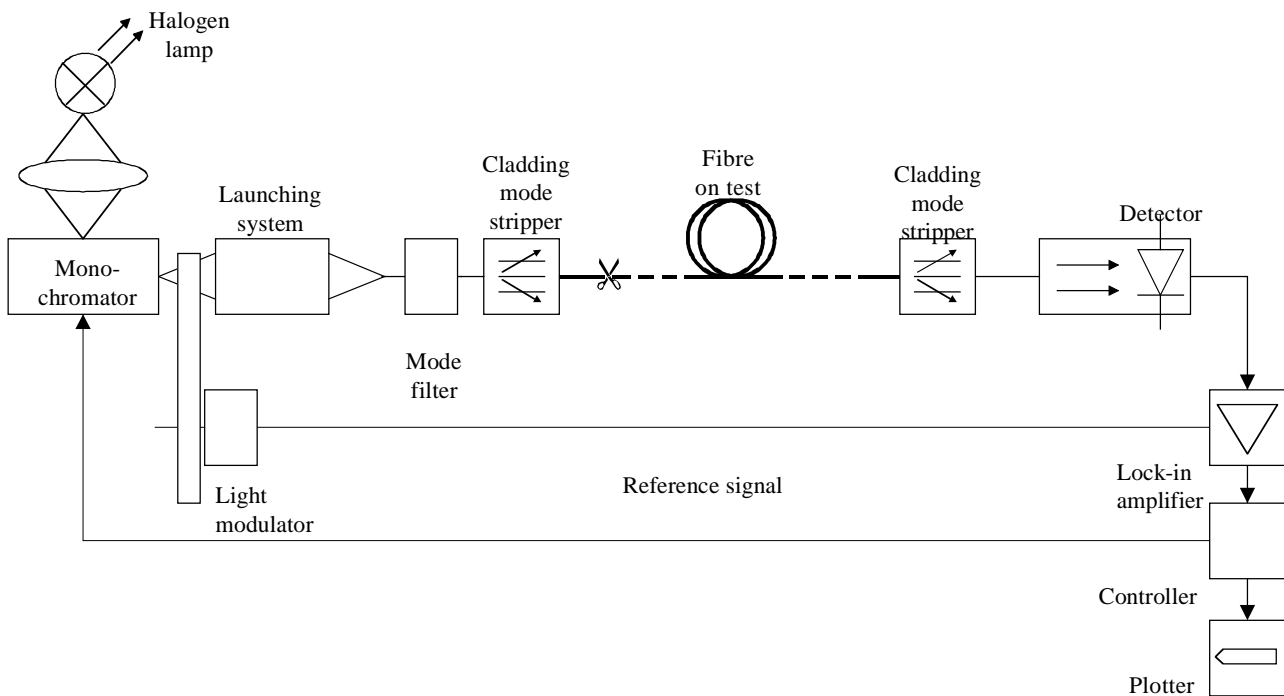
The cut-back technique is a direct application of the definition in which the power levels P_1 and P_2 are measured at two points of the fibre without change of input conditions. P_2 is the power emerging from the far end of the fibre and P_1 is the power emerging from a point near the input after cutting 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 equipments, to obtain one loss or the loss spectrum measurements respectively, are shown as examples in Figure 12.



a) Arrangement of test equipment to make one loss measurement



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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 1-4 and 1-5.

2.4.1.4 Presentation of the results

- 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

A test method for the attenuation coefficient of single-mode optical fibre based on bidirectional backscattering measurements is described. This technique can also be applied to check the attenuation uniformity, optical continuity, physical discontinuities, splice losses and the length of the fibre.

Unidirectional backscattering measurements can be adopted in particular cases, e.g. verification of the backscatter slope variation in cabled fibres.

Procedures for the calibration of backscattering equipment are provided in IEC Document XXXX.

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. In addition, adjustment of the pulse width may be required to obtain a compromise between resolution and dynamic range.

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

An example of apparatus is shown in Figure 13 a).

2.4.2.2.2 Optical source

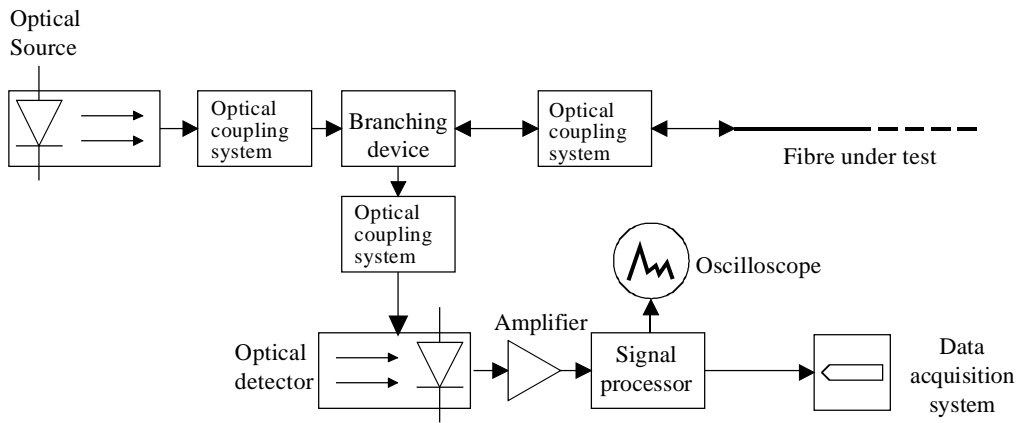
Use a stable, high power optical source of appropriate wavelengths and record them. The pulse width and repetition rate should be consistent with the desired resolution and the length of the fibre.

2.4.2.2.3 Optical coupling system

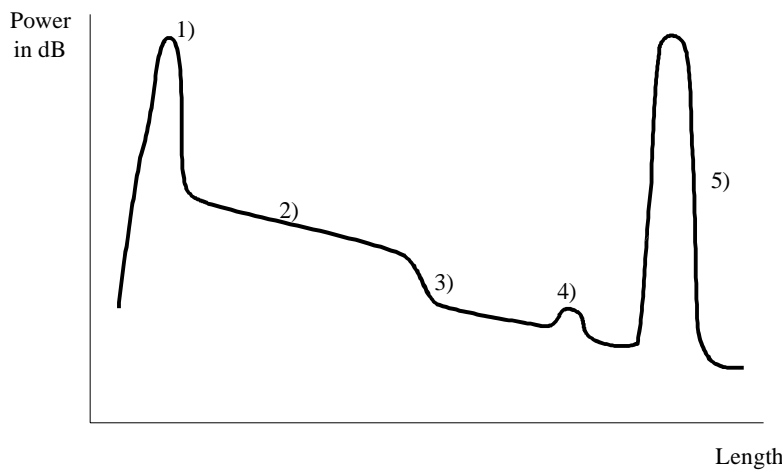
An optical system for an efficient coupling of the beam into the fibre under test, the branching device or the optical detector shall be used. Various devices, such as index matching materials, can be added to reduce Fresnel reflections.

2.4.2.2.4 Branching device

A branching device is needed to couple the source radiation into the fibre and the backscattered radiation onto the detector, while avoiding a direct source-detector coupling. Avoid using devices with polarization-dependent properties.



a) Schematic of apparatus



b) Example of a unidirectional backscattering loss curve

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Figure 13/G.650 – The backscattering technique

2.4.2.2.5 Optical detector

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

2.4.2.2.6 Amplifier

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

2.4.2.2.7 Signal processor

A signal processor able to improve the signal-to-noise ratio, to calculate the attenuation curve from the two unidirectional backscattering loss curves, and to provide a logarithmic response in the detection system is required. An oscilloscope for a direct view of the backscattering trace and a data acquisition system to store the measurement results can be connected to the signal processor.

2.4.2.2.8 Cladding mode stripper

See 2.4.1.2.5.

2.4.2.2.9 Fibre sample configuration

The measurement may be made with the fibre in a number of fibre configurations (e.g. as cabled fibre, on a suitable shipping spool or as required for the reference text method).

2.4.2.3 Measurement procedure

- a) Align the fibre under test to the optical coupling system.
- b) Measure two unidirectional backscattering loss curves, one from each end of the fibre. Figure 13 b) shows an example of such a unidirectional curve. Each backscattering loss curve is analysed by the signal processor and recorded on a logarithmic scale, avoiding the parts at the two ends of the curves, due to the reflections of the coupling and branching devices and by the fibre ends [see parts 1) and 5) in Figure 13 b)].
- c) Evaluate the length, L_f , of the fibre from the time interval between the two ends of the backscattering loss curve, T_f , and the group delay index, N , of the fibre as: $L_f = c \cdot T_f / N$ (c being the free space light speed).
- d) Obtain the bidirectional backscattering loss curve using the two measured and recorded unidirectional backscattering loss curves, according to the procedure outlined in the following:

Let $a(x)$ and $b(z)$ be the functions describing the two unidirectional backscattering loss curves expressed in dB, with x and z being the distances from the fibre ends nearest the respective launch site. The bidirectional backscattering loss curve is given by:

$$y(x) = \frac{a(x) - b(L_f - x)}{2} \quad (2-12)$$

- e) Obtain the end-to-end fibre attenuation coefficient according to the procedure outlined in the following:

The attenuation coefficient, $A(x_0, x_1)$, for a fibre segment defined by the end positions x_0 and x_1 (with $x_0 < x_1$) is given by:

$$A(x_0, x_1) = \frac{y(x_0) - y(x_1)}{x_1 - x_0} \quad (2-13)$$

This expression may be evaluated by a least squares linear fit of the data between x_0 and x_1 .

The end-to-end fibre attenuation coefficient is determined in the same way as equation 2-13 with the data points as close as possible to the end positions. However, these points should be outside the dead zone area and the end reflection area [see Figure 13 b), areas 1) and 5)].

2.4.2.4 Presentation of the results

- a) Test set-up arrangement.
- b) Kind of signal processing used.
- c) Date of test.
- d) Test specimen identification and length.
- e) Pulse width.
- f) Test wavelength(s).

- g) End-to-end fibre attenuation coefficient in dB/km.
- h) Bidirectional backscattering loss curve.

NOTE – Unidirectional backscattering measurements are obtained with the function $a(x)$ alone. The complete analysis of the recorded unidirectional backscattering loss curves [Figure 13 b)] shows that, independently from the attenuation measurements, many phenomena can be monitored using the backscattering technique including:

- 1) Reflection originated by the branching and coupling devices at the input end of the fibre.
- 2) Zone of invariant backscattered slope.
- 3) Discontinuity due to local defect, splice or coupling.
- 4) Backscattering slope variation with length.
- 5) Fluctuation at the output end of the fibre.
- 6) Attenuation change, for example with temperature.

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 14); 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 2.4.3.3.2.

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.

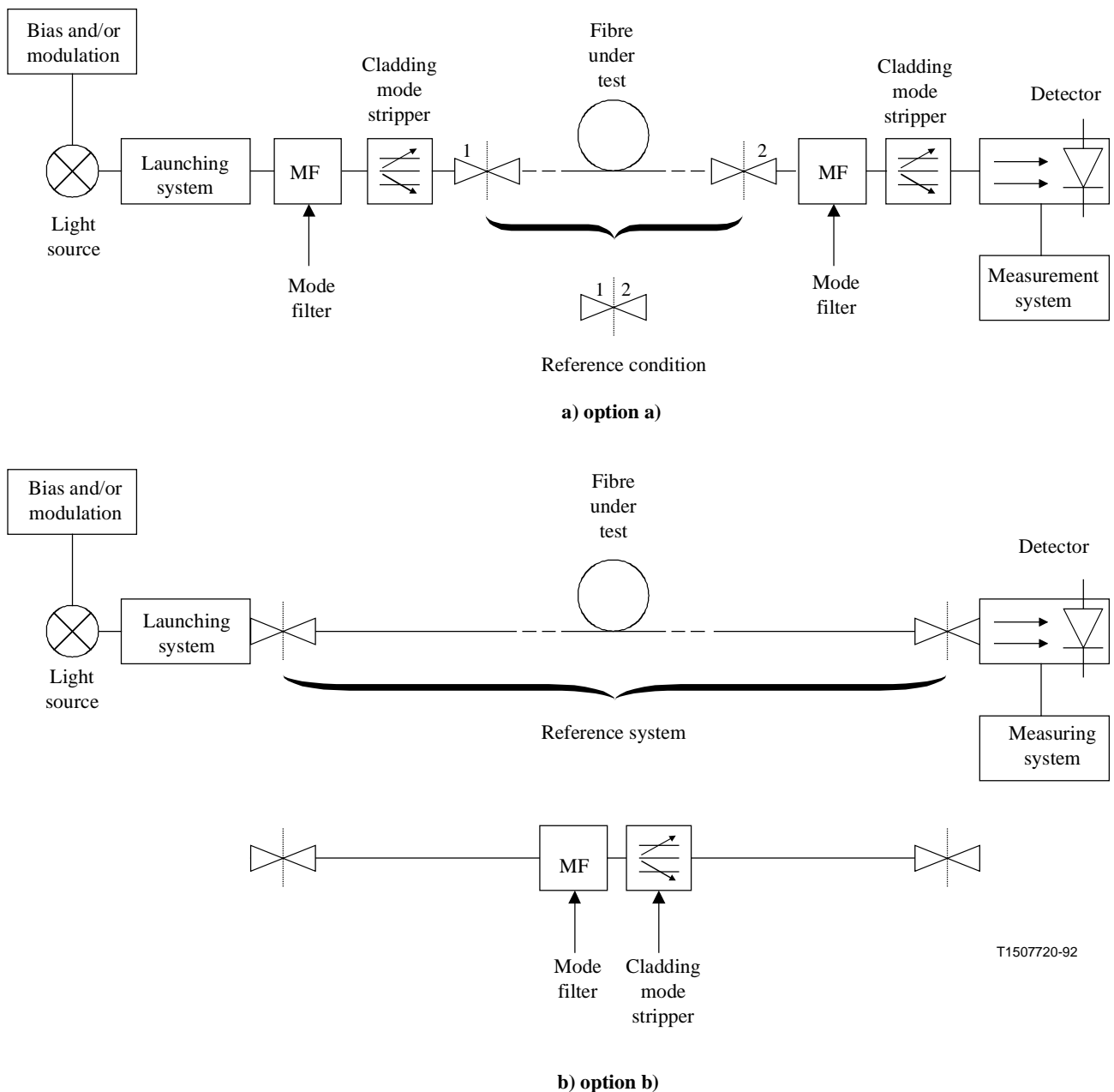


Figure 14/G.650 – Typical arrangements for the insertion loss technique

2.4.3.2 Test apparatus

The schematic diagram of the test apparatus is shown in Figure 14. 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.

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 far-field intensity of the fibre under test.

The system can employ lenses and a fibre positioner; alternatively the light can be launched in a step-index multimode 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 point 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 multimode 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)

$$A = 10 \log \frac{P_1(\lambda)}{P_2(\lambda)} + C_r - C_1 - C_2 \text{ (dB)} \quad (2-14a)$$

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)

$$A = 10 \log \frac{P_1(\lambda)}{P_2(\lambda)} \text{ (dB)} \quad (2-14b)$$

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:

$$A = 10 \log \frac{P_1(\lambda)}{P_2(\lambda)} - C_a \text{ (dB)} \quad (2-15)$$

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

- 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 repeatability (the connection loss repeatability 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

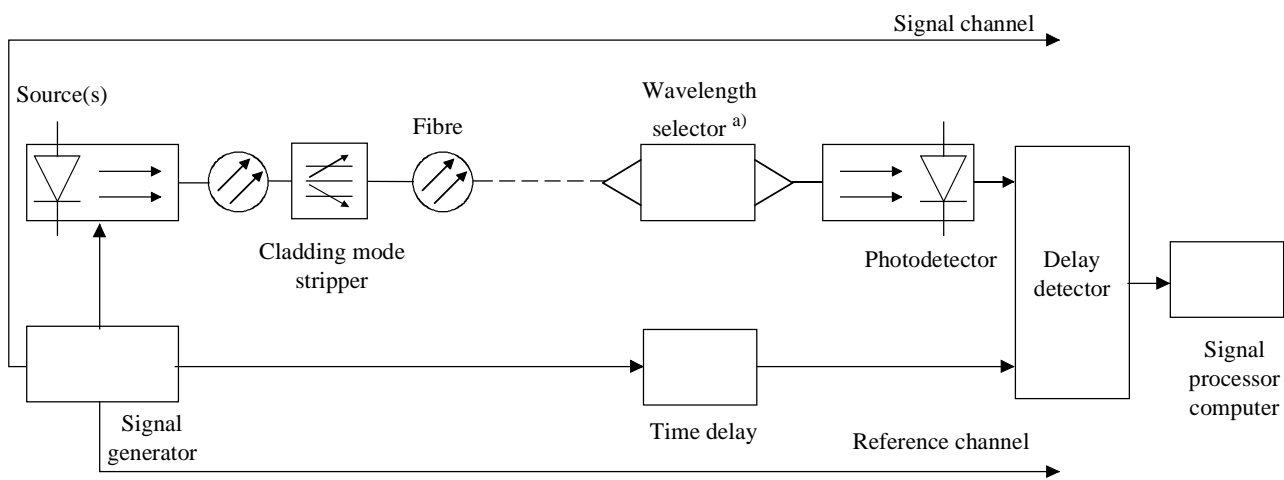
The fibre chromatic dispersion coefficient is derived from the measurement of the relative group delay experienced by the various wavelengths during propagation through a known length of fibre.

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 15.



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^{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 tunable 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.

If a mathematical fit (such as equations 2-16, 2-18 or 2-20) is made to the data, at least one data point must be within 100 nm of λ_0 .

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 photodetector 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 $\tau = \phi/(2\pi f)$, 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:

$$\tau(\lambda) = \tau_0 + \frac{S_0}{8} \left(\lambda - \frac{\lambda_0^2}{\lambda} \right)^2 \quad (2-16)$$

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:

$$D(\lambda) = \frac{S_0}{4} \left(\lambda - \frac{\lambda_0^4}{\lambda^3} \right) \quad (2-17)$$

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

NOTE 1 – These equations for $\tau(\lambda)$ and $D(\lambda)$ are sufficiently accurate over the 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.

NOTE 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 2-17 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:

$$\tau(\lambda) = \tau_0 + \frac{S_0}{2}(\lambda - \lambda_0)^2 \quad (2-18)$$

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:

$$D(\lambda) = (\lambda - \lambda_0)S_0 \quad (2-19)$$

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 .

NOTE 1 – These equations for $\tau(\lambda)$ and $D(\lambda)$ are sufficiently accurate over the 1500-1600 nm range. They are not meant to be used in the 1310 nm region.

NOTE 2 – Alternatively, the chromatic dispersion coefficient can be measured directly, for example by the differential phase shift method. In this case, a straight line (2-19) 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:

$$\tau(\lambda) = \tau_{1550} + (S_{1550} / 2)(\lambda - 1550)^2 + D_{1550}(\lambda - 1550) \quad (2-20)$$

Here τ_{1550} is the 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:

$$D(\lambda) = S_{1550}(\lambda - 1550) + D_{1550} \quad (2-21)$$

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.

NOTE 1 – These equations for $\tau(\lambda)$ and $D(\lambda)$ are sufficiently accurate over the 1500-1600 nm range. They are not meant to be used in the 1310 nm region.

NOTE 2 – Alternatively, the chromatic dispersion coefficient can be measured directly, for example by the differential phase shift method. In this case, a straight line (2-21) shall be fitted directly to the dispersion coefficient for determining S_{1550} and D_{1550} .

2.5.1.4 Presentation of the results

- 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 for fibres covered by Recommendations G.652 and G.653 or the values of the chromatic dispersion coefficient and the dispersion slope at $\lambda = 1550$ nm for fibres covered by Recommendation G.654.

- 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

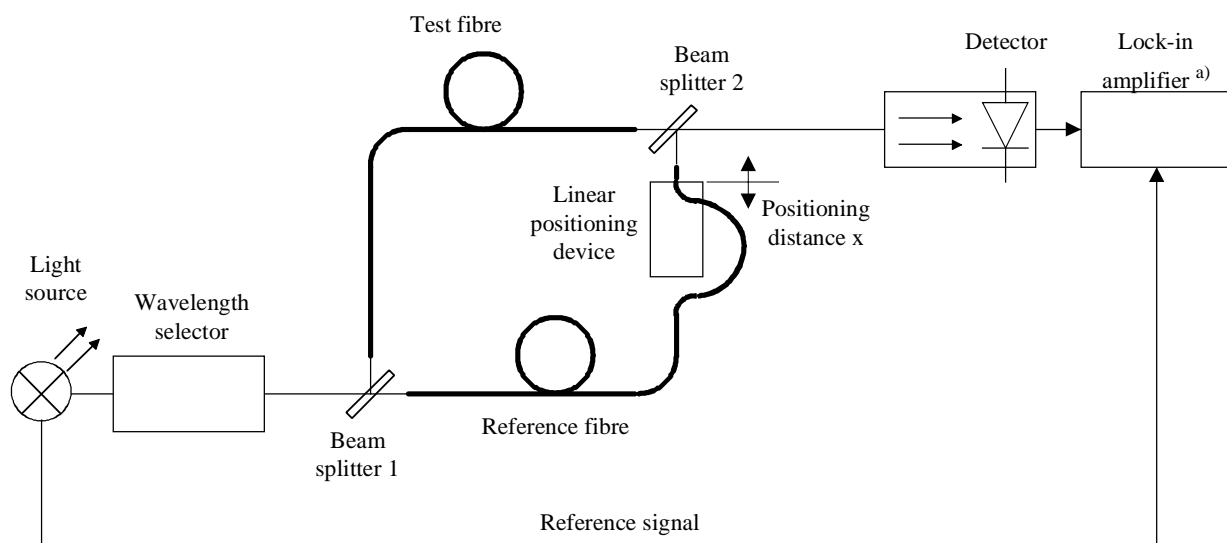
The interferometric test method allows the chromatic dispersion to be measured, using a short piece of fibre (several metres). This offers the possibility of measuring the longitudinal chromatic dispersion homogeneity of optical fibres. Moreover, it is possible to test the effect of overall or local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

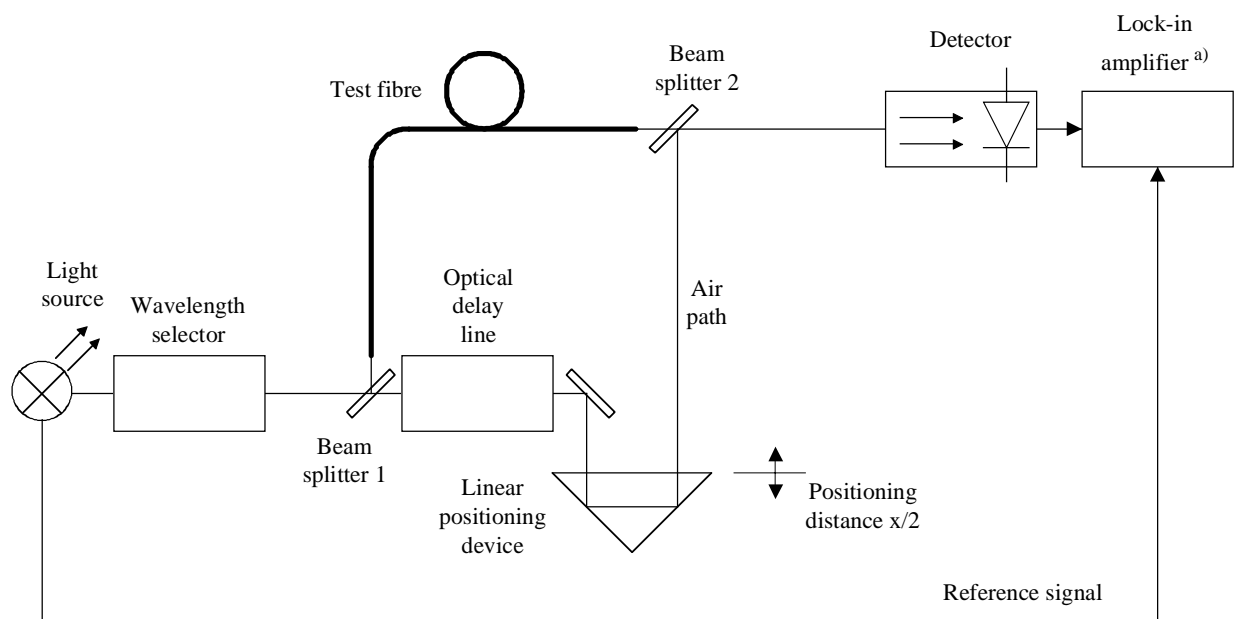
Schematic diagrams of the test apparatus using a reference fibre and an air path reference are shown in Figures 16 and 17, respectively.



^{a)} When needed.

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Figure 16/G.650 – Schematic diagram of measurement set-up with reference fibre



a) When needed.

T1507750-92

Figure 17/G.650 – Schematic diagram of measurement set-up with 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.

If a mathematical fit (such as equations 2-16, 2-18 or 2-20) is made to the data, at least one data point must be within 100 nm of λ_0 .

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 for wavelength λ_0 (Figure 18) determines the group delay difference $\Delta\tau_g(\lambda_i)$ between the reference path and the test path as follows:

$$\Delta\tau_g(\lambda_i) = \frac{x_0 - x_i}{c_0} \quad (2-22)$$

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

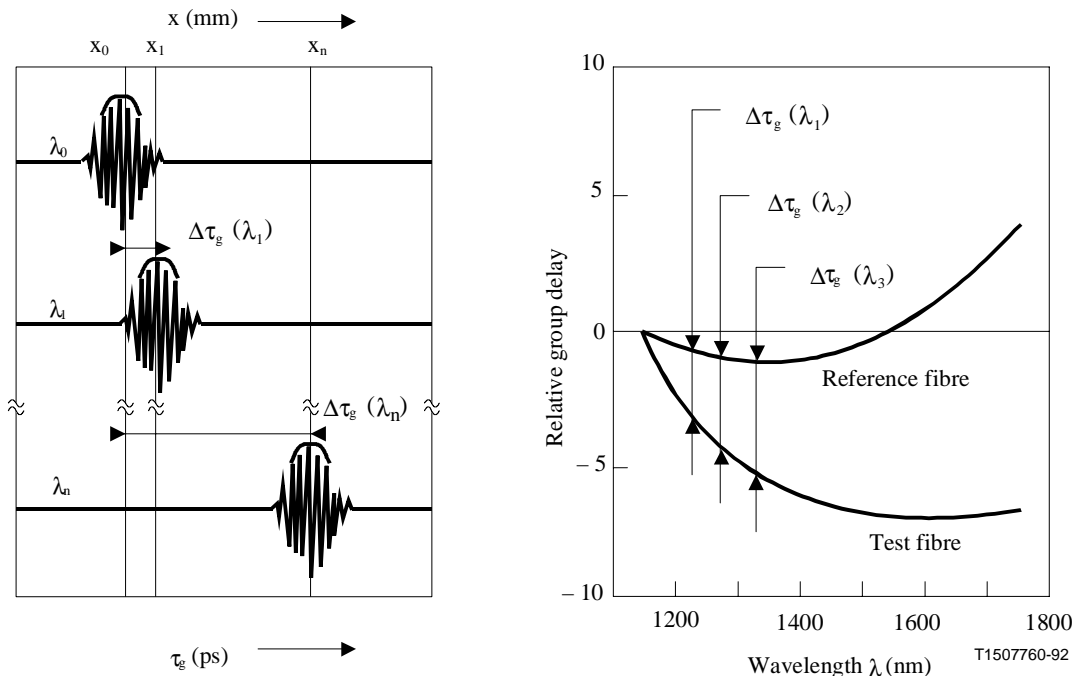


Figure 18/G.650 – Determination of the spectral group delay

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 2-16.

The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated Sellmeier expression 2-17.

NOTE – Equations 2-16 and 2-17 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 2-18. The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated quadratic expression 2-19.

NOTE – Equations 2-18 and 2-19 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 2-20. The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated quadratic expression 2-21.

NOTE – Equations 2-20 and 2-21 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

- 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 for fibres covered by Recommendations G.652 and G.653 or the values of the chromatic dispersion coefficient and the dispersion slope at $\lambda = 1550$ nm for fibres covered by Recommendation G.654.
- 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 15.

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

A 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.

If a mathematical fit (such as equations 2-16, 2-18 or 2-20) is made to the data, at least one data point must be within 100 nm of the zero-dispersion wavelength λ_0 .

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 photodetector 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 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.

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 2-16.

The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated Sellmeier expression 2-17.

NOTE – Equations 2-16 and 2-17 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 2-18. The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated quadratic expression 2-19.

NOTE – Equations 2-18 and 2-19 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 2-20. The chromatic dispersion coefficient $D(\lambda) = d\tau/d\lambda$ can be determined from the differentiated quadratic expression 2-21.

NOTE – Equations 2-20 and 2-21 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

- 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 for fibres covered by Recommendations G.652 and G.653 or the values of the chromatic dispersion coefficient and the dispersion slope at $\lambda = 1550$ nm for fibres covered by Recommendation G.654.
- 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: $23 \pm 5^\circ \text{C}$ 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:

$$\sigma = E(1 + c\epsilon)\epsilon \quad (2-23)$$

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 fibre stress is calculated from the applied tension, T , as:

$$\sigma = \frac{(1 - F)T}{\pi a^2} \quad (2-24)$$

where $2a$ is the diameter of the glass fibre ($125 \mu\text{m}$) and F is the fraction of the tension borne by the coating. F is given by:

$$F = \frac{\sum_{j=1}^n E_j A_j}{E_g \pi a^2 + \sum_{j=1}^n E_j A_j} \quad (2-25)$$

n is the number of coating layers;

E_j is the modulus of the j th coating layer;

A_j is the nominal cross-sectional area of the j th coating layer;

E_g is the modulus of the glass fibre.

NOTE – Coating moduli are typically characterized by manufacturers.

2.6.1.1.1 Proofstress parameters

- a) The proofstress, σ_p , is specified to control the length of the surviving sections of the fibre. The stress applied during the proofstress, σ_a , is illustrated in Figure 19. The load and unload times, t_l and t_u , and the dwell-time, t_d are also shown. The tensile load shall be applied for as short a time as possible, yet sufficiently long to ensure the glass experiences the proofstress.
- b) The applied stress shall exceed the specified proofstress at all times. The unload time shall be controlled to be less than some maximum values to be agreed between user and manufacturer to control unloading damage.

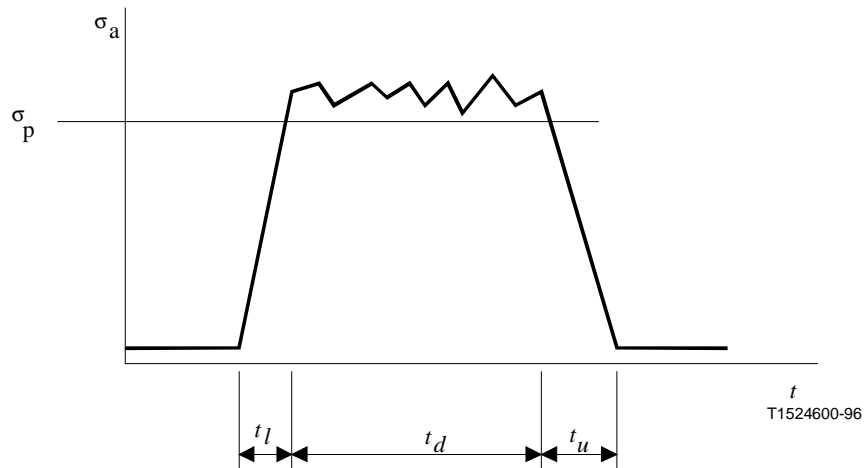


Figure 19/G.650 – Stress σ versus time t during prooftesting

2.6.1.2 Test apparatus

2.6.1.2.1 Operating procedure requirements

- In the pay-out and take-up regions, the fibre is maintained with a low value of stress typically not exceeding 10% of the proofstress (see Figure 19).
- In the loading region, fibre stress ramps up from a low stress level to the full proofstress. The load time is t_l .
- In the prooftest region, the applied proofstress, σ_a , is maintained at values greater than the specified proofstress, σ_p .
- In the unloading region, fibre stress ramps down from the applied stress to a low value of stress. The time to unload the fibre is t_u .
- The unloading time is controlled to be less than a maximum value to be agreed between user and manufacturer. It can be varied by changing the processing speed or by the gripping capstan design.
- The capstans and other support pulleys shall be designed and operated to ensure that they do not induce excessive damage. The gripping capstans shall be capable of maintaining the applied stress without inducing additional damage from slipping.

2.6.1.2.2 Proofstress machines

- Braked-capstan machine* (Figure 20)

The fibre is paid out with constant, low tension. Also the rewinding after the proofstress is done with constant tension. The levels of the pay-off and take-up tensions are adjustable.

The proofstress load is applied to the fibre between the brake and drive capstans by creating a speed difference between the capstans. Two belts are used to prevent slippage at the capstans. The high precision tension gauge measures the load on the fibre and controls the speed difference to achieve the required proofstress load. The load level and operating speed of the equipment can be independently set.

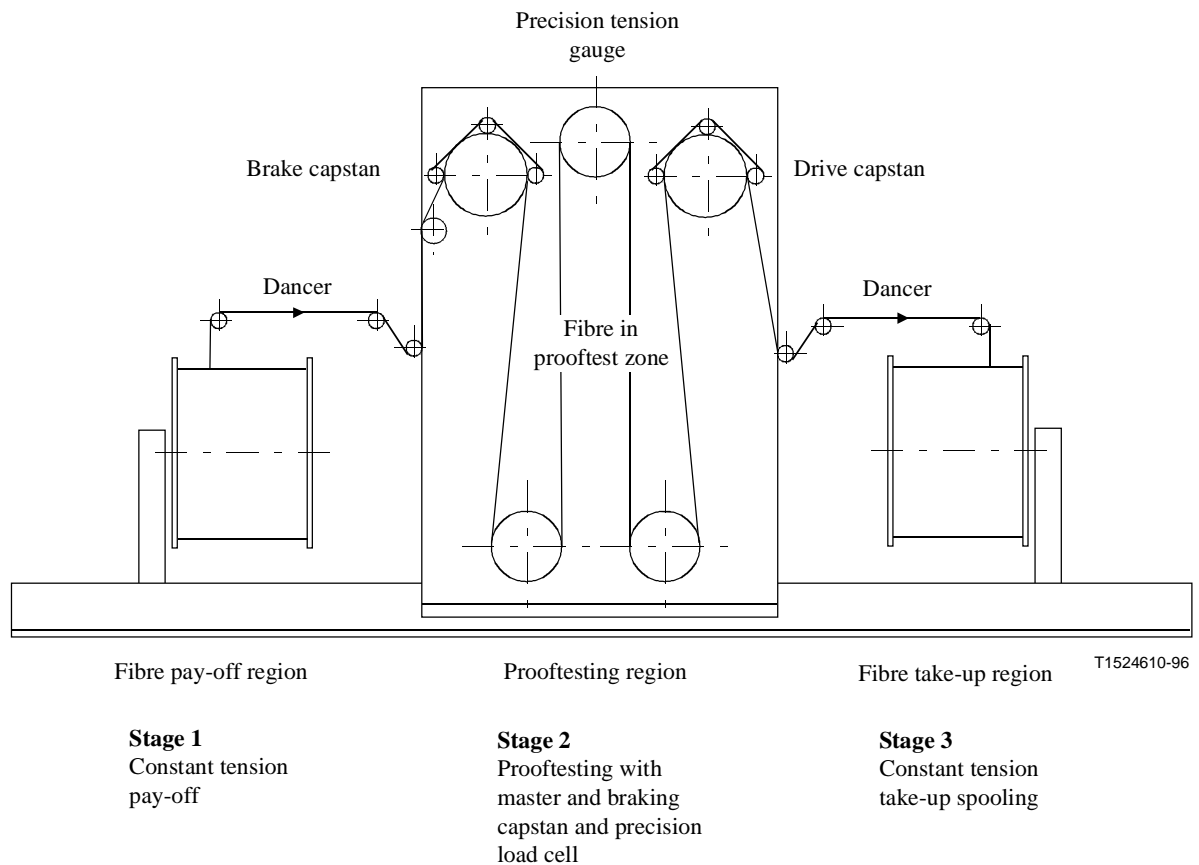
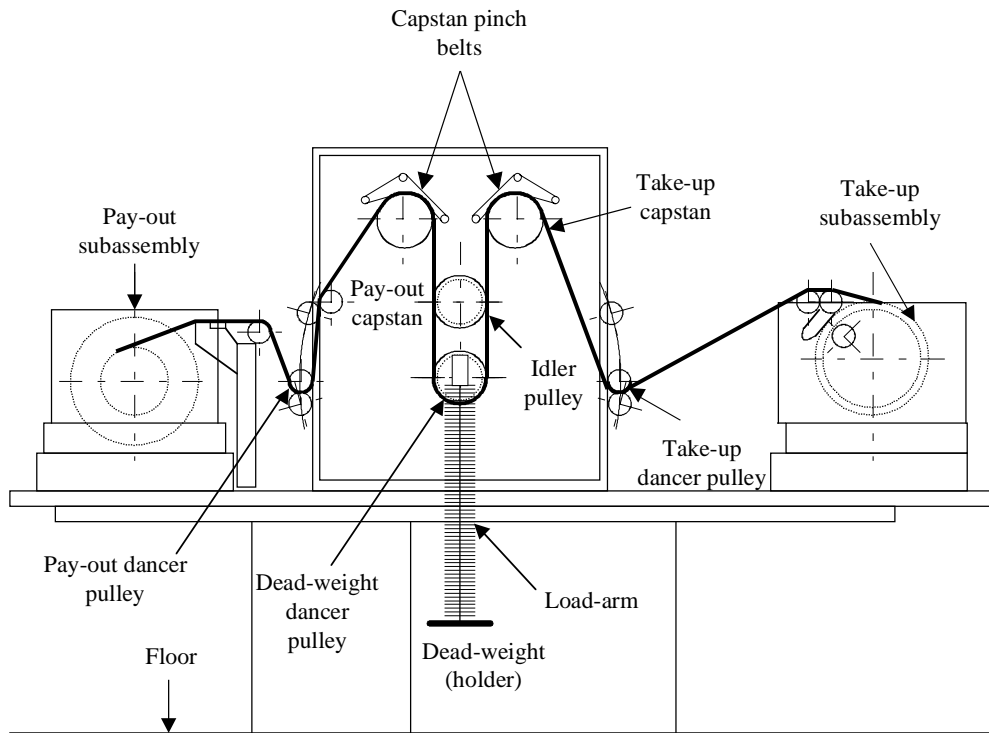


Figure 20/G.650 – Typical arrangement of a braked-capstan proofstest machine

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.



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Figure 21/G.650 – Dead-weight proof test 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 short sections at the ends in which all requirements, i.e. maximum unloading time, may not be met. This end allowance length, typically less than 50 m, shall be presented.
- b) Fibre failure after proof testing shall be evidenced by complete breakage. Examination methods include visual inspection and OTDR measurements. After broken areas are removed, the surviving fibre lengths are considered to have passed the proof test procedure.

2.6.1.3.2 Calculation

If the machine is calibrated in tension, the stress is calculated from equation 2-24. Strain may be obtained from equation 2-23.

2.6.1.4 Presentation of the results

- a) General description of the apparatus.
- b) Fibre identification.
- c) Average applied proof stress.
- d) Maximum unloading time.
- e) Dwell-time.
- f) End allowance length.

2.7 Test methods for polarization mode dispersion

2.7.1 The Jones matrix eigenanalysis technique

2.7.1.1 General

This test method describes a procedure for measuring the Polarization Mode Dispersion (PMD) of single-mode optical fibres. The measurement result is obtained from a single series of Jones matrix measurements performed at intervals across a wavelength range. It can be applied to both short and long fibres, regardless of the degree of polarization mode coupling. Under some circumstances, repeated measurements may be necessary to achieve satisfactory precision. This method is restricted to wavelengths greater than or equal to that at which the fibre is effectively single-mode.

2.7.1.2 Test apparatus

See Figure 22 for a schematic diagram of the key components in a typical measurement system.

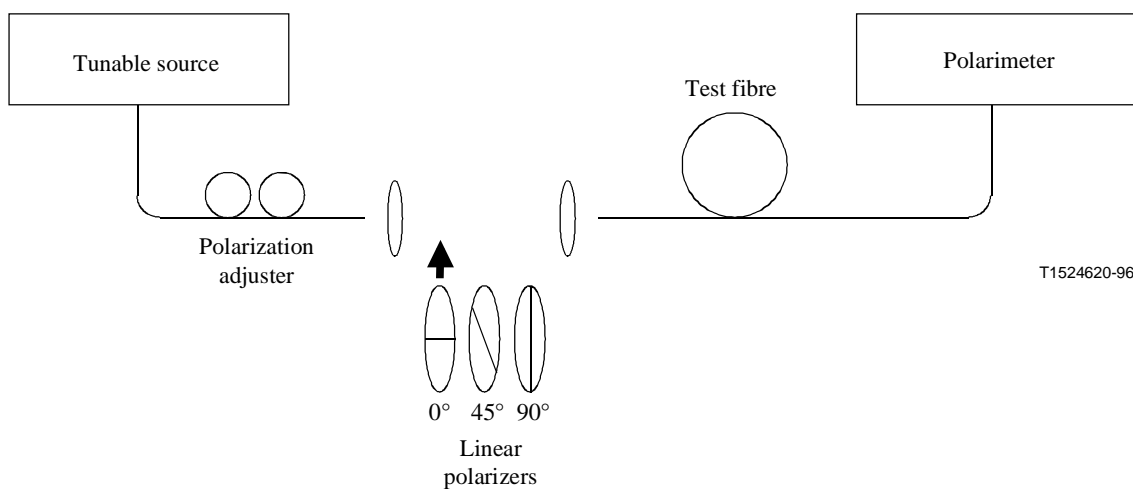


Figure 22/G.650 – Schematic diagram of equipment (typical)

2.7.1.2.1 Light source

Use a single-line laser or narrow-band source which is tunable across the intended measurement wavelength range. The spectral distribution shall be narrow enough so that the light emerging from the test fibre remains polarized under all conditions of the measurement. Degree of Polarization (DOP) of 90% or greater is preferred, although measurements may be performed with values as low as 25% with reduced precision. For a given value of differential group delay $\Delta\tau$, the lowest degree of polarization which can result is given by:

$$DOP = 100e^{-\frac{1}{4\ln 2} \left(\frac{\pi c \Delta\tau \Delta\lambda_{FWHM}}{\lambda_0^2} \right)^2} \quad (2-26)$$

assuming a Gaussian spectrum of width $\Delta\lambda_{FWHM}$ centred at λ_0 . DOP is expressed in per cent.

2.7.1.2.2 Polarization adjuster

A polarization adjuster follows the laser and is set to provide roughly circularly polarized light to the polarizers, so that the polarizers never cross polarization with their input light. Adjust polarization as follows. Set the tunable laser wavelength to the centre of the range to be measured. Insert each of the three polarizers into the beam and perform three corresponding power measurements at the output of

the polarizers. Adjust the source polarization via the polarization adjuster such that the three powers fall within approximately a 3 dB range of one another. In an open beam version of the set-up, a waveplate may perform the polarization adjustment.

2.7.1.2.3 Polarizers

Three linear polarizers at relative angles of approximately 45 degrees are arranged to be inserted into the light beam in turn. The actual relative angles shall be known.

2.7.1.2.4 Input optics

An optical lens system or single-mode fibre pigtail may be employed to excite the test fibre.

2.7.1.2.5 Fibre pigtail

If pigtails are used, interference effects due to reflections should be avoided. This may require index matching materials or angled cleaves. The pigtails shall be single-mode.

2.7.1.2.6 Optical lens system

If an optical lens system is used, some suitable means, such as a vacuum chuck, shall be used to stably support the input end of the fibre.

2.7.1.2.7 Cladding mode stripper

Remove any cladding mode power from the test fibre. Under most circumstances, the fibre coating will perform this function; otherwise, employ a device that extracts cladding mode power.

2.7.1.2.8 Output optics

Couple all power emitted from the test fibre to the polarimeter. An optical lens system, a butt splice to a single-mode fibre pigtail or an index-matched coupling made directly to the detector system are examples of means that may be used.

2.7.1.2.9 Polarimeter

Use a polarimeter to measure the three output states of polarization corresponding to insertion of each of the three polarizers. The wavelength range of the polarimeter shall include the wavelengths produced by the light source.

2.7.1.3 Measurement procedure

The test sample shall be a known length of a single-mode optical fibre which may or may not be cabled. The sample and pigtails shall be fixed in position at a nominally constant temperature throughout the measurement. Temperature stability of the test device may be observed by viewing the output state of polarization of the test fibre on a Poincare sphere display. In a time period corresponding to an adjacent pair of Jones matrix measurements, output polarization change should be small relative to the change produced by a wavelength increment.

NOTE – Although the test sample is normally a fibre, this test can also be performed on discrete components. In this case, PMD coefficient is not relevant.

When it is important to minimize additional mode coupling, uncabled fibre shall be supported in some manner (usually on a reel having a minimum wind radius of 150 mm) with essentially zero fibre tension (typically less than 15 g).

Alternative fibre conditions (e.g. fibre shipping spool) may be used in case it has been demonstrated that comparable results are obtained.

Couple the light source through the polarization adjuster to the polarizers.

Couple the output of the polarizers to the input of the fibre under test.

Couple the output of the fibre under test to the input of the polarimeter.

Select the wavelength interval $\Delta\lambda$ over which Jones matrix measurements are to be performed. The maximum allowable value of $\Delta\lambda$ (around λ_0) is set by the requirement:

$$\Delta\tau_{\max}\Delta\lambda \leq \frac{\lambda_0^2}{2c} \quad (2-27)$$

where $\Delta\tau_{\max}$ is the maximum expected DGD within the measurement wavelength range. For example, the product of maximum DGD and wavelength interval shall remain less than 4 ps.nm at 1550 nm and less than 2.8 ps.nm at 1300 nm. This requirement ensures that from one test wavelength to the next, the output state of polarization rotates less than 180 degrees about the principal states axis of the Poincare sphere. If a rough estimate of $\Delta\tau_{\max}$ cannot be made, perform a series of sample measurements across the wavelength range, each measurement using a closely spaced pair of wavelengths appropriate to the spectral width and minimum tuning step of the optical source. Multiply the maximum DGD measured in this way by a safety factor of three, substitute this value for $\Delta\tau_{\max}$ in the above expression and compute the value of $\Delta\lambda$ to be used in the actual measurement. If there is concern that the wavelength interval used for a measurement was too large, the measurement may be repeated with a smaller wavelength interval. If the shape of the curve of DGD versus wavelength and the mean DGD are essentially unchanged, the original wavelength interval was satisfactory.

Gather the measurement data. At the selected wavelengths, insert each of the polarizers and record corresponding Stokes parameters from the polarimeter.

2.7.1.4 Calculations or interpretation of result

2.7.1.4.1 Calculations

From the Stokes parameters, compute the response Jones matrix at each wavelength. For each wavelength interval, compute the product of the Jones matrix $\mathbf{T}(\omega + \Delta\omega)$ at the higher optical frequency and the inverse Jones matrix $\mathbf{T}^{-1}(\omega)$ at the lower optical frequency. Radian optical frequency ω is expressed in radians per second and is related to optical frequency ν by $\omega = 2\pi\nu$. Find the DGD $\Delta\tau$ for the particular wavelength interval from the following expression:

$$\Delta\tau = \left| \frac{\text{Arg}\left(\frac{\rho_1}{\rho_2}\right)}{\Delta\omega} \right| \quad (2-28)$$

where ρ_1 and ρ_2 are the complex eigenvalues of $\mathbf{T}(\omega + \Delta\omega) \mathbf{T}^{-1}(\omega)$ and Arg denotes the argument function, that is $\text{Arg}(\eta e^{i\theta}) = \theta$. For purposes of data analysis, each DGD value is taken to represent the differential group delay at the midpoint of the corresponding wavelength interval. The series of DGD values obtained from a series of wavelength intervals across a wavelength range comprises a single measurement.

2.7.1.4.2 Display of DGD versus wavelength

Data may be plotted in x-y format with DGD on the vertical axis and wavelength on the horizontal axis as shown in Figure 23. Data may also be displayed in a histogram as shown in Figure 24.

Fibre PMD test results
44 km SMF at room temperature

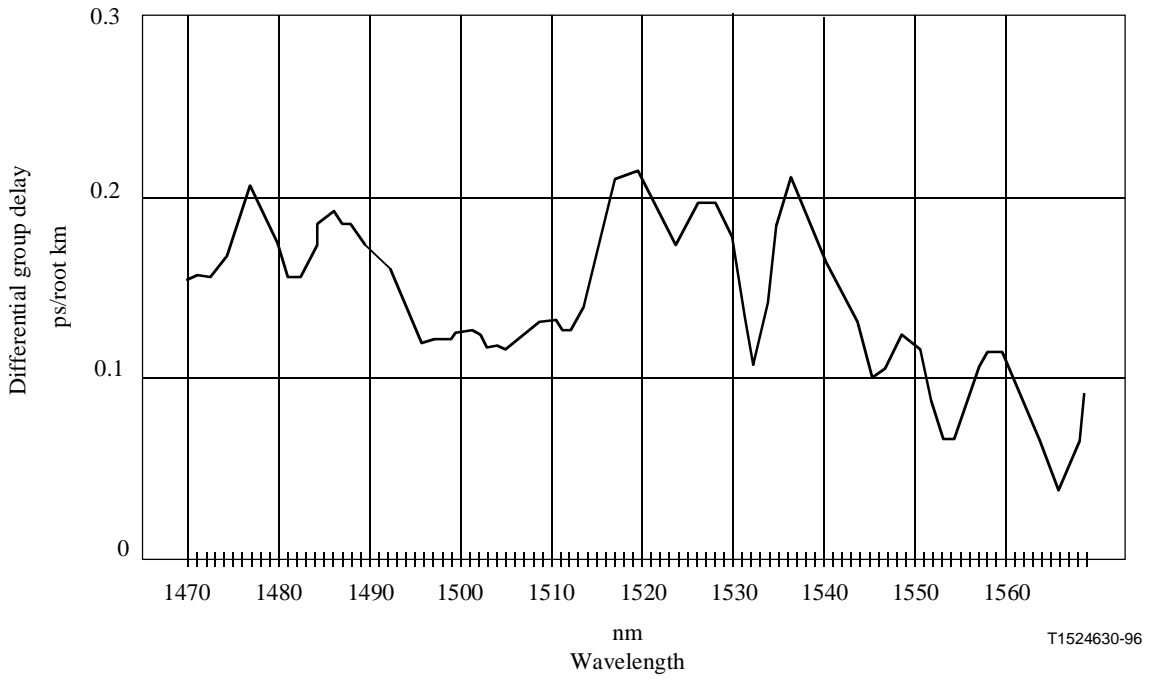
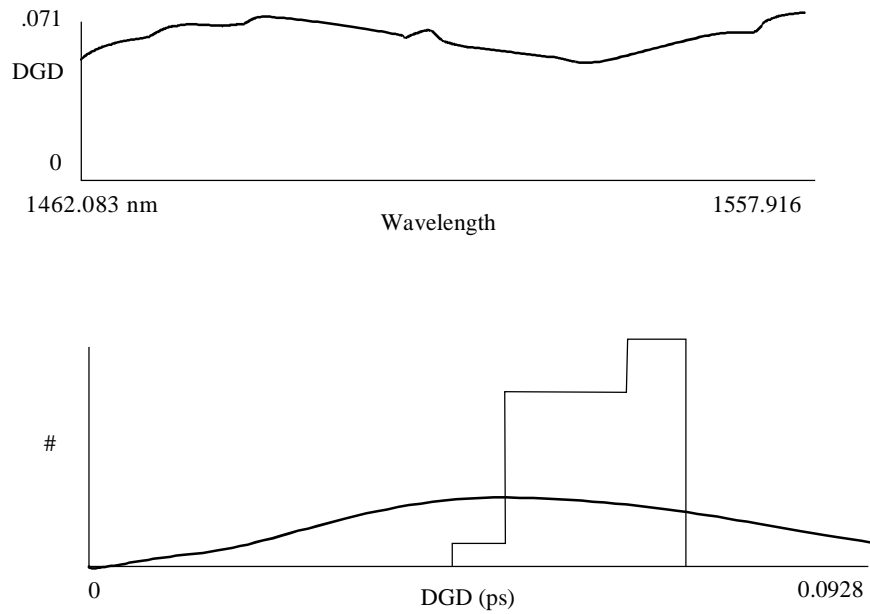
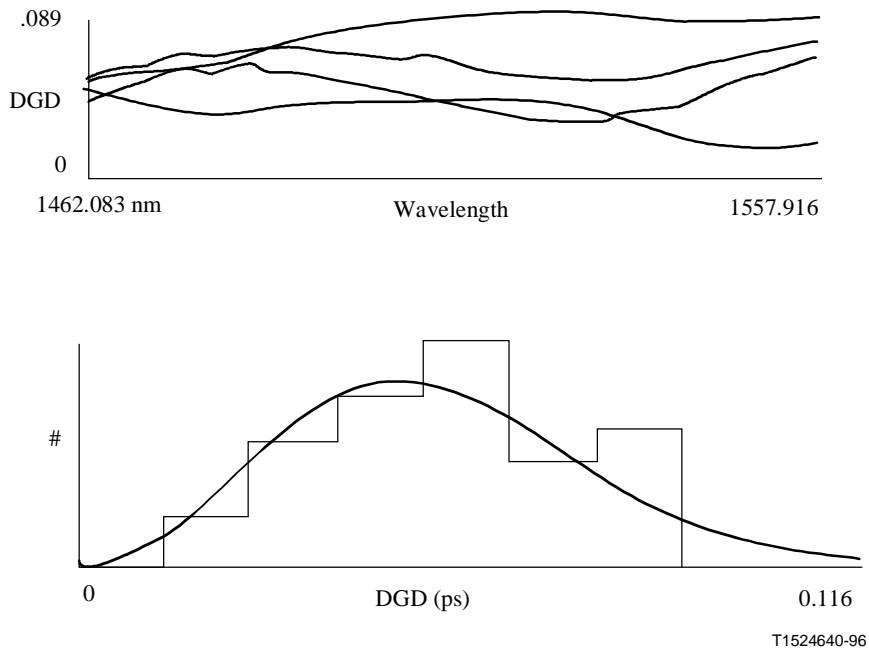


Figure 23/G.650 – Measured DGD of 44 km single-mode fibre



a) Single 24-interval measurement of a spooled fibre



b) Four 24-interval measurements of the same spool conducted at different oven temperatures

Figure 24/G.650 – Examples of DGD data in histogram format

A Maxwell curve is superimposed on each histogram. Curves of measured DGD versus wavelength are shown for reference.

2.7.1.4.3 Average DGD

The expected PMD value $\langle \Delta\tau \rangle_\lambda$ of a single measurement is simply the average of the DGD measurement values corresponding to the wavelength intervals. If multiple measurements are performed under different conditions to increase the sample size, the ensemble average is used.

2.7.1.4.4 PMD coefficient

PMD may be expressed in terms of the short- or long-fibre PMD coefficient, depending upon the type of mode coupling exhibited by the fibre sample. In the absence of mode coupling, use the "short-length" coefficient given in equation 1-9. For fibres with random mode coupling, use the "long-length" coefficient given in equation 1-10.

If the standard deviation of $\Delta\tau$ across the measurement wavelength range is less than 1/10 of the mean, the test fibre is considered to exhibit negligible mode coupling (a "deterministic" device) and PMD may be expressed by the "short-length" PMD coefficient $\langle\Delta\tau\rangle/L$.

2.7.1.4.5 Presentation of the results

- a) Identification of the fibre and/or cable measured.
- b) Test length.
- c) Polarization mode dispersion in ps. If the degree of mode coupling is known, the PMD may be given in ps/km (negligible mode coupling) or ps/km^{1/2} (random mode coupling).
- d) The wavelength range over which the measurement was performed, and the wavelength step size.
- e) The physical configuration of the fibre or cable sample.
- f) Mode coupling type, e.g. deterministic, semi-random or random.
- g) When an average PMD has been determined from repeated measurements of the sample, record the number of measurements performed.
- h) The number of DGD values obtained from a single measurement across the wavelength range, corresponding to the number of wavelength intervals.

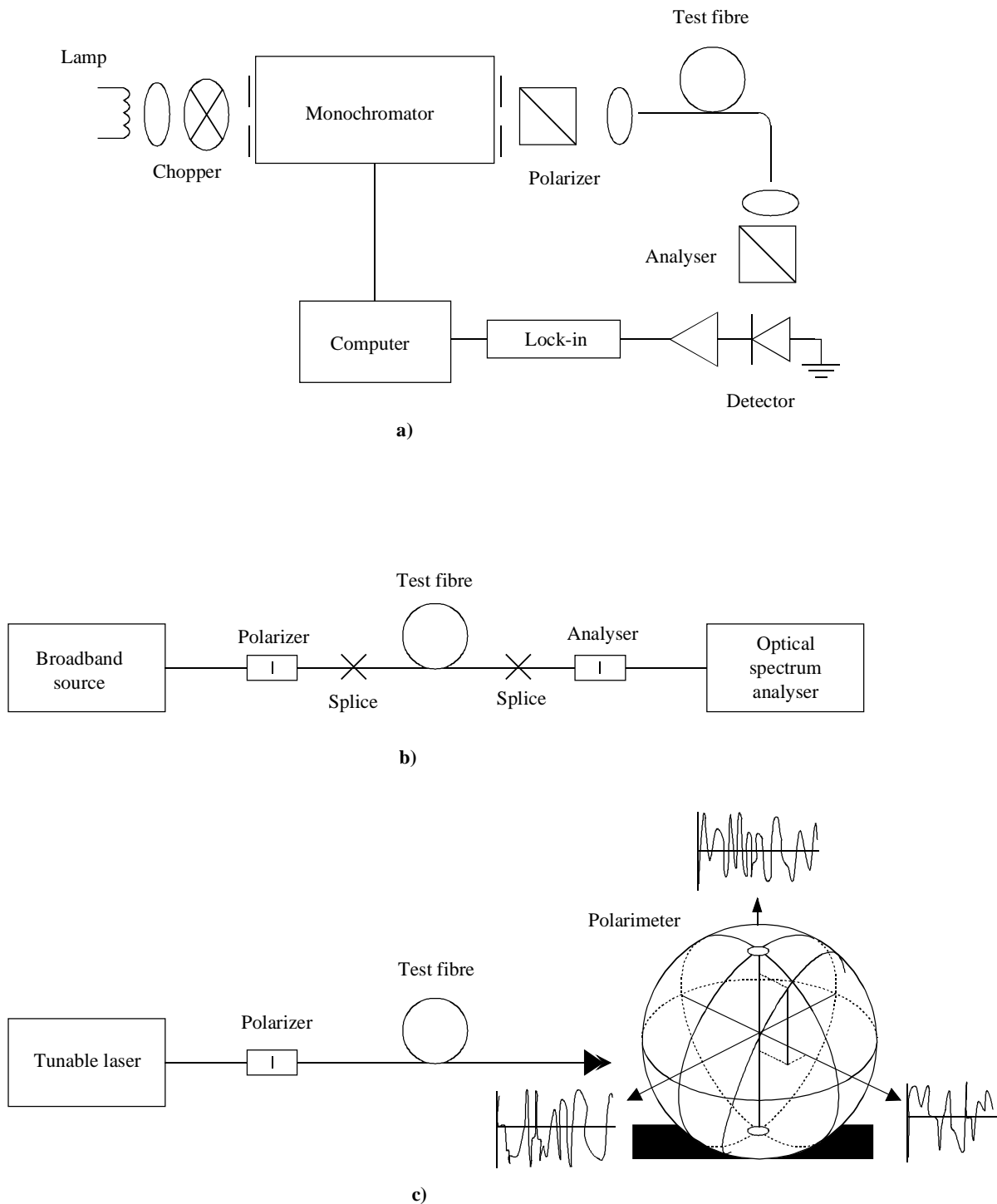
2.7.2 The fixed analyser technique

2.7.2.1 General

This test method describes a procedure for measuring the Polarization Mode Dispersion (PMD) of single-mode optical fibres. It produces a single measurement value that represents the PMD over the measurement wavelength range of typically a few hundred nanometers. The method can be applied to both short and long fibres in the limits of both zero and strong polarization mode coupling. Under some circumstances, repeated measurements may be necessary to achieve satisfactory precision using this method. The procedure is restricted to wavelengths greater than or equal to that at which the fibre is effectively single-mode.

2.7.2.2 Test apparatus

See Figure 25 for a schematic diagram of the key components in a typical measurement system.



T1524650-96

Figure 25/G.650 – Schematic diagram of equipment (typical)

2.7.2.2.1 Light source

Use a light source which emits radiation at the intended measurement wavelengths, such as a broadband lamp, light emitting diode(s) or tunable laser(s). It shall be stable in intensity and spectral distribution over a time period long enough to perform the measurement.

2.7.2.2.2 Monochromator

Obtain a specified set of test wavelengths by filtering the light source with a monochromator as in Figure 25 a), or by using an optical spectrum analyser as the detector, as in Figure 25 b). This filtering is not needed when the source is a tunable laser [see Figure 25 c)]. The spectral distribution must be narrow enough to avoid major depolarization of the signal under the influence of the PMD of the fibre under test (see 2.7.2.4.1.4 and 2.7.2.4.2.8).

2.7.2.2.3 Input optics

An optical lens system or single-mode fibre pigtail may be employed to excite the test fibre. The power coupled into the fibre shall be stable for the duration of the test. If pigtails are used, interference effects due to reflections should be avoided. This may require index matching materials or angled cleaves. The pigtails shall be single-mode.

If an optical lens system is used, some suitable means, such as a vacuum chuck, shall be used to stably support the input end of the fibre.

2.7.2.2.4 Cladding mode stripper

Remove any cladding mode power from the test fibre. Under most circumstances, the fibre coating will perform this function; otherwise employ a device that extracts cladding mode power.

2.7.2.2.5 Output optics

All power emitted from the test fibre must be coupled onto the active region of the detection system (see Figure 25). An optical lens system, a butt splice to a single-mode fibre pigtail or an index-matched fibre-to-fibre coupling made directly to the detection system are examples of means that may be used.

2.7.2.2.6 Signal detection

For signal detection, use an optical detector which is linear and stable over the range of intensities and measurement times that are encountered in performing the measurement. A typical system might include synchronous detection by a chopper/lock-in amplifier, an optical power meter, an optical spectrum analyser or a polarimeter. To use the entire spectral range of the source, the detection system must have a wavelength range which includes the wavelengths produced by the light source.

2.7.2.2.7 Polarizer and analyser

The polarizer at the fibre input (Figure 25) is needed only if the launch beam is not already polarized (usually a 3 dB extinction ratio is sufficient). The angular orientation of the polarizers is not critical, but should remain fixed throughout the measurement. With weak mode coupling, some adjustment of the polarizer orientation may be helpful in maximizing the amplitude of the oscillations in Figure 26 a). Alternatively, this may be achieved by rotation of the fibre(s) at splices or connectors.

The analyser is not needed when a polarimeter is used for signal detection [Figure 25 c)].

2.7.2.3 Measurement procedure

The test sample shall be a known length of a single-mode optical fibre which may or may not be cabled. The sample and pigtails must be fixed in position at a nominally constant temperature throughout the measurement.

NOTE – Although the test sample is normally a fibre, this test can also be performed on discrete components. In this case, PMD coefficient is not relevant.

Temperature stability of the test device may be observed by measuring the output power from the fibre at a fixed wavelength, with the output analyser in place. In a time period corresponding to a

typical complete measurement, the output power change should be small relative to the changes produced by a wavelength increment.

When it is important to minimize additional mode coupling, uncabled fibre shall be supported in some manner (usually on a reel having a minimum wind radius of 150 mm) with essentially zero fibre tension (typically less than 15 g).

Alternative fibre conditions (e.g. fibre shipping spool) may be used in case it has been demonstrated that comparable results are obtained.

Couple the input end of the fibre to the light source. Couple the output radiation from the fibre under test to the detection system.

By making appropriate adjustments to the monochromator, optical spectrum analyser or tunable laser, inject each designated test wavelength λ in turn into the fibre. The choice of wavelengths depends on the designated wavelength scan range and also on the analysis method (see 2.7.2.4.1 and 2.7.2.4.2).

Record the corresponding output signal for each wavelength. This process shall be accomplished without changing the launch and detector conditions. Call the received power $P_A(\lambda)$, where A denotes the presence of the analyser.

Remove the analyser from the beam and repeat the monochromator scan. Call this received power $P_{TOT}(\lambda)$. This latter power can be used to eliminate the spectral dependence of the measurement system components and the test fibre loss. Typical plots of the ratio:

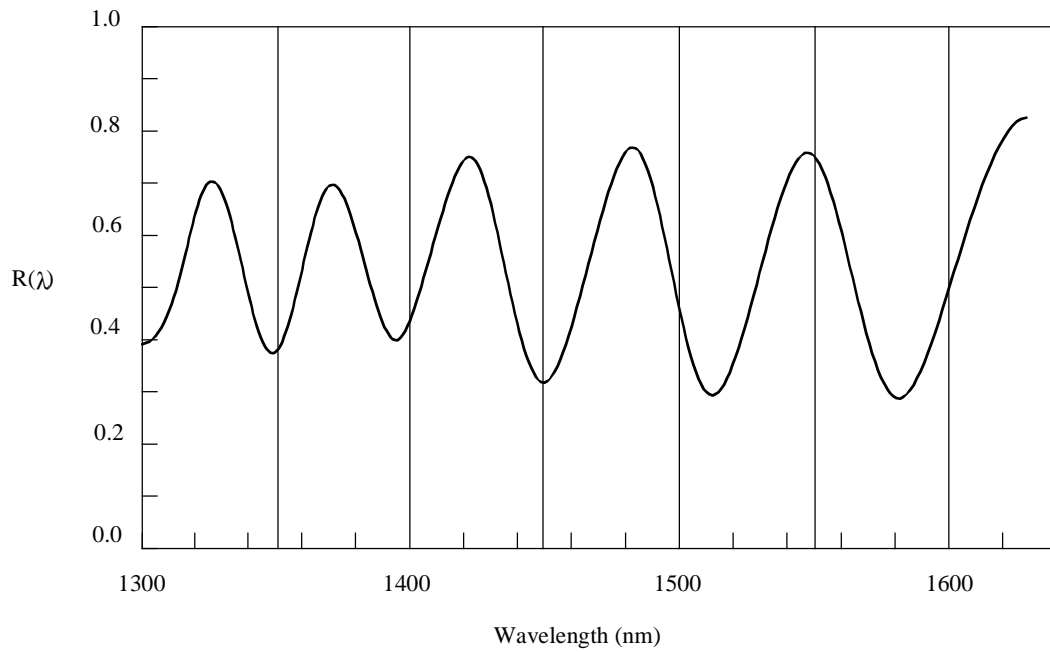
$$R(\lambda) = \frac{P_A(\lambda)}{P_{TOT}(\lambda)} \quad (2-29)$$

are shown in Figure 26.

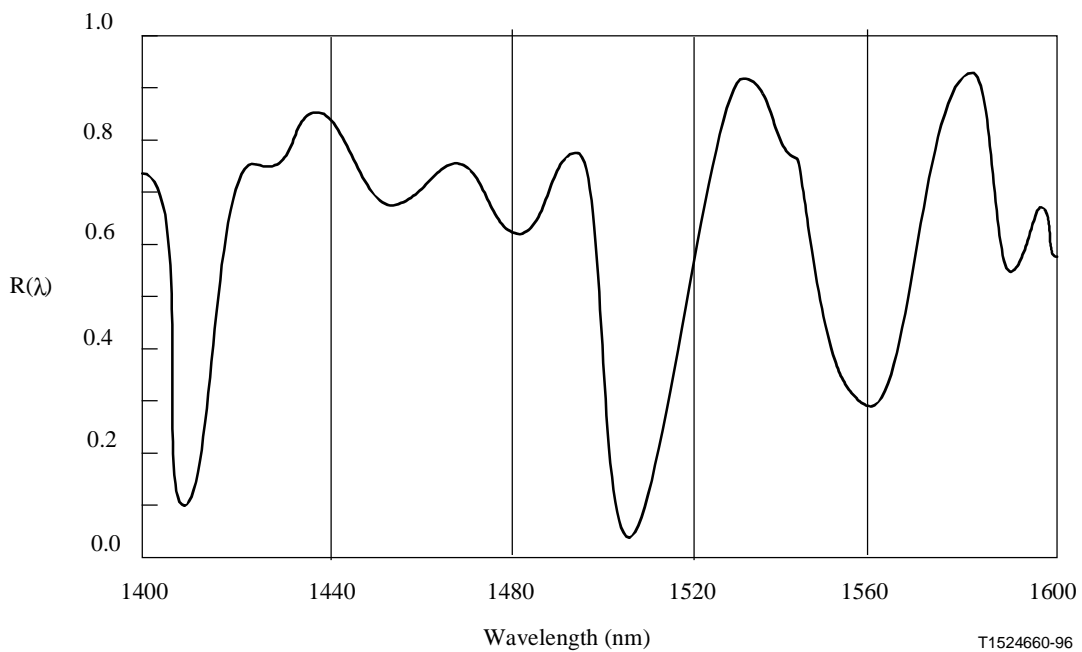
An alternative procedure is to leave the analyser in place, but rotate it 90° with respect to the orientation used above. Calling the power received in this case $P_{ROT}(\lambda)$, then:

$$R(\lambda) = \frac{P_A(\lambda)}{P_A(\lambda) + P_{ROT}(\lambda)} \quad (2-30)$$

If a polarimeter is used as the detection element, the normalized Stokes parameters are measured versus wavelength. The three spectral functions are independent of the received power and are analysed by the same methods applied to $R(\lambda)$ (see 2.7.2.4.1 and 2.7.2.4.2). Each normalized Stokes parameter then leads to a value of $\langle \Delta\tau \rangle$.



a) Weak mode coupling



b) Strong mode coupling

Figure 26/G.650 – Typical data obtained in measuring PMD

2.7.2.4 Calculations or interpretation of results

One of the following two methods (2.7.2.4.1 and 2.7.2.4.2) shall be used for calculating PMD from the measurement data.

2.7.2.4.1 Extrema counting

2.7.2.4.1.1 PMD

$R(\lambda)$ should be obtained at evenly spaced wavelength intervals. E is the number of extrema within the window $\lambda_1 < \lambda < \lambda_2$. Alternatively, λ_1 and λ_2 may be chosen to coincide with extrema, in which case E is the number of extrema (including the ones at λ_1 and λ_2) minus one.

$$\langle \Delta\tau \rangle = \frac{k E \lambda_1 \lambda_2}{2 (\lambda_2 - \lambda_1) c} \quad (2-31)$$

where c is the speed of light in vacuum, k is a mode coupling factor which equals 1.0 in the absence of mode coupling (the equation 1-9 regime) and 0.82 in the limit of strong mode coupling (the equation 1-10 regime).

If a polarimeter is used as the detection element, take as the final value of $\langle \Delta\tau \rangle$ the average of the values derived from the three normalized Stokes parameter responses. The value of $\langle \Delta\tau \rangle$ provided by equation 2-31 or the average of the three values of $\langle \Delta\tau \rangle$ derived from polarimetric detection can be used in equation 1-9 or 1-10 (whichever is appropriate for the particular sample) to calculate the PMD coefficient. The resulting value is to be interpreted as an average over the wavelength range $\lambda_1 < \lambda < \lambda_2$.

2.7.2.4.1.2 Accuracy

The best accuracy is obtained by making $(\lambda_2 - \lambda_1)$ large enough to insure that $E \gg 1$. This is especially important when there is strong mode coupling [Figure 26 b)] and less so otherwise [Figure 26 a)]. Values of E in the range of 7 to 40 are typical. When E is at the low end of this range, the percentage of uncertainties in both E and the PMD become large. At the upper end of the range, instrumental broadening may result in some adjacent peaks not being resolved.

Ideally, the scan window should be centred on the fibre's wavelength of use, and the window made wide enough to ensure that E is greater than about 10 for the maximum PMD value of interest (where pass/fail is an issue).

2.7.2.4.1.3 Peak identification

The identification of extrema in $R(\lambda)$ can be more difficult in the presence of noise and/or strong mode coupling. This can be seen in the example of Figure 26 b). An algorithm with the following features is useful in identifying extrema:

- 1) A polynomial is fitted to several adjacent points of $R(\lambda)$ to provide a smoothed curve.
- 2) An extremum is defined as a point where the wavelength derivative of this smoothed curve changes sign.

Additional robustness can be built into the peak identification algorithm if needed.

2.7.2.4.1.4 Spectral resolution

To insure that all features in the optical spectrum are adequately resolved, the spectral resolution $\Delta\lambda$ should satisfy:

$$\Delta\lambda / \lambda < (8\nu\Delta\tau)^{-1} \quad (2-32)$$

where ν is the optical frequency. $\Delta\lambda$ is the instrumental spectral width or the wavelength step size, whichever is larger. For λ in the vicinity of 1550 nm, equation 2-32 reduces to the condition that $\Delta\lambda$ (nm) should be less than the reciprocal of $\Delta\tau$ (ps).

2.7.2.4.2 Fourier analysis

2.7.2.4.2.1 Overview

In this method a Fourier analysis of $R(\lambda)$, usually expressed in the domain of optical frequency, ν , is used to derive PMD. The Fourier transform transforms this optical frequency domain data to the time domain. The Fourier transform yields direct information on the distribution of light arrival times $\delta\tau$. This data is post-processed as described below to derive the expected PMD, $\langle\Delta\tau\rangle$, for the fibre under test. This method is applicable to fibres with weak or strong mode coupling (refer to 2.7.2.4.2.4 and 2.7.2.4.2.5, respectively).

2.7.2.4.2.2 Data pre-processing and Fourier transformation

To use this method, the Fourier transform normally requires equal intervals in optical frequency so that $R(\lambda)$ data is collected (as described in 2.7.2.3) at λ values such that they form equal intervals in the optical frequency domain. Alternatively, data taken at equal λ intervals may be fitted (for example, by using a cubic spline fit) and interpolation used to generate these points, or more advanced spectral estimation techniques used. In each instance, the ratio $R(\lambda)$ at each λ value used is calculated using equations 2-29 or 2-30 as appropriate.

Zero-padding or data interpolation and DC level removal may be performed on the ratio data, $R(\lambda)$. Windowing the data may also be used as a pre-conditioning step before the Fourier transform. The Fourier transformation is now carried out to yield the amplitude data distribution $P(\delta\tau)$ for each value of $\delta\tau$.

2.7.2.4.2.3 Transform data fitting

Fourier transformed data at zero $\delta\tau$ has little meaning since, unless carefully removed, DC components in $R(\lambda)$ may be partially due to insertion loss of the analyser for example. When the DC level is not removed, up to two data points are generally bypassed (not used) in any further calculations. A variable, j , is defined so that the "first valid bin" above zero $\delta\tau$ that is included in calculations corresponds to $j = 0$.

In order to remove measurement noise from subsequent calculations, $P(\delta\tau)$ is compared to a threshold level T_1 , typically set to 200% of the r.m.s. noise level of the detection system. It is now necessary to determine whether the fibre is weakly or strongly mode coupled.

If it is found that the first X valid points of $P(\delta\tau)$ are all below T_1 , this indicates that $P(\delta\tau)$ must have discrete spike features characteristic of weakly coupled fibres. The value of X is equal to three, unless zero-padding is used in the Fourier analysis. In that case, the value of X can be determined from $3 * (\text{number of original data points}) / (\text{total length of array after zero-padding})$. Use subclause 2.7.2.4.2.4 to calculate PMD. If this is not the case, proceed to calculate PMD using subclause 2.7.2.4.2.5 or 2.7.2.4.2.6.

2.7.2.4.2.4 PMD calculation for fibres with weak mode coupling

For a weakly coupled fibre (e.g. a high birefringence fibre) or for a birefringent component, $R(\lambda)$ resembles a chirped sine wave [Figure 26 a)]. Fourier transformation will give a $P(\delta\tau)$ output containing a discrete spike at a position corresponding to the relative pulse arrival time, $\delta\tau$, the centroid of which is the PMD value $\langle\Delta\tau\rangle$.

To define the spike centroid $\langle \Delta\tau \rangle$, those points where $P(\delta\tau)$ exceeds a second predetermined threshold level T_2 , typically set to 200% of the r.m.s. noise level of the detection system, are used in the equation:

$$\langle \Delta\tau \rangle = \frac{\sum_{e=0}^{M'} [P_e(\delta\tau)\delta\tau_e]}{\sum_{e=0}^{M'} [P_e(\delta\tau)]} \quad (2-33)$$

where $M'+1$ is the number of data points of P within the spike which exceed T_2 . $\langle \Delta\tau \rangle$ in equation 2-33 is typically quoted in picoseconds. If the device under test is a fibre of length L , the PMD coefficient may be calculated using equation 1-9. If no spike is detected (i.e. $M'=0$), then PMD is zero. Other parameters such as the r.m.s. spike width and/or spike peak value may be reported.

If the device under test contains one or more birefringent elements, more than one spike will be generated. For a number n concatenated fibres/devices, $2^{(n-1)}$ spikes will be obtained.

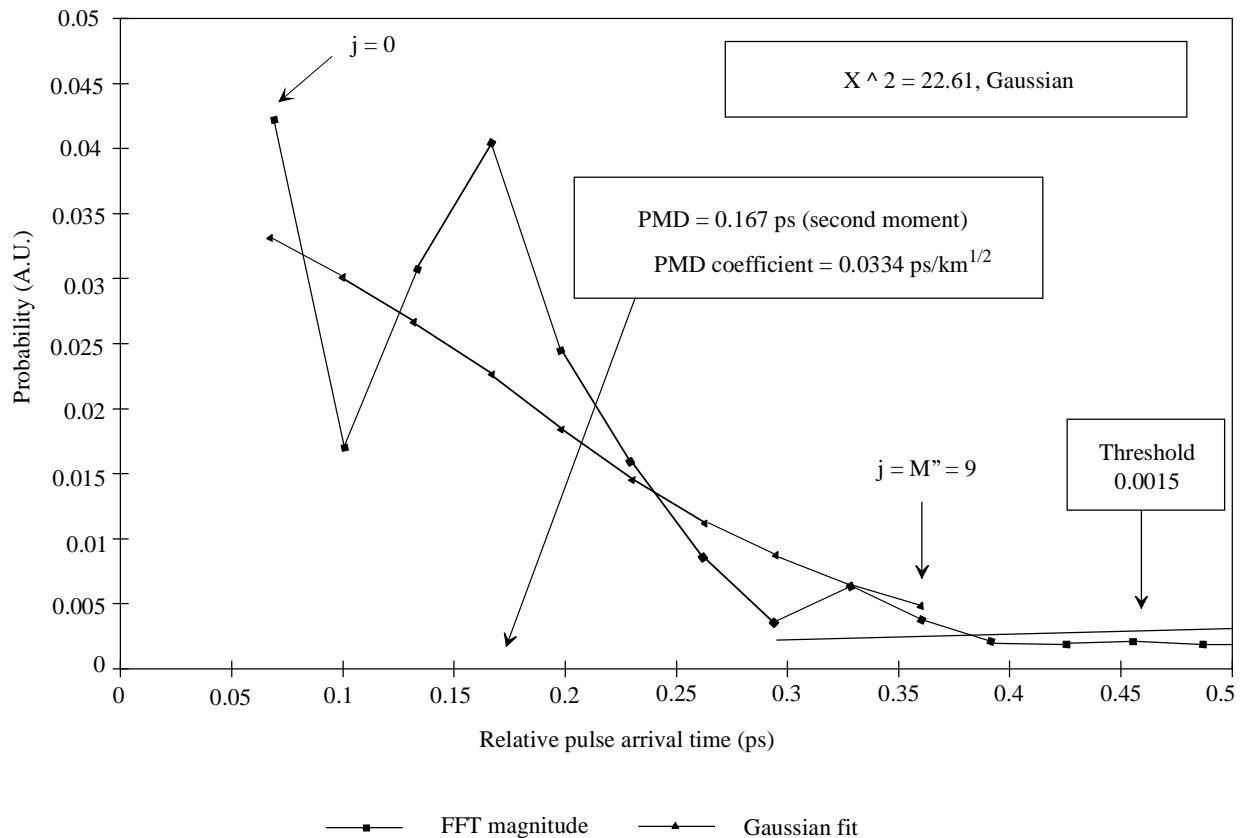
2.7.2.4.2.5 PMD calculation for fibres with strong mode coupling

In instances of strong mode coupling, $R(\lambda)$ becomes a complex waveform similar to Figure 26 b), the exact characteristics being based on the actual statistics of the coupling process within the fibre/cable. The Fourier transformed data now becomes a distribution $P(\delta\tau)$ representing the autocorrelation of the probability distribution of light pulse arrival times, $\delta\tau$, in the fibre.

Counting up from $j=0$, determine the first point of P which exceeds T_1 , and which is followed by at least X data points which fall below T_1 . This point represents the last significant point in (i.e. the "end" of) the distribution $P(\delta\tau)$, for a strongly mode-coupled fibre, that is not substantially affected by measurement noise. The $\delta\tau$ value for this point is denoted $\delta\tau_{\text{last}}$, and the value of j at $\delta\tau_{\text{last}}$ is denoted M'' . This fibre is strongly mode coupled. The square root of the second moment, σ_R , of this distribution defines the fibre PMD $\langle \Delta\tau \rangle$, and is given by:

$$\langle \Delta\tau \rangle = \sigma_R = \left\{ \frac{\sum_{j=0}^{M''} [P_j(\delta\tau)\delta\tau_j^2]}{\sum_{j=0}^{M''} [P_j(\delta\tau)]} \right\}^{1/2} \quad (2-34)$$

The $\langle \Delta\tau \rangle$ value given by equation 2-34 is typically quoted in picoseconds. An example of the Fourier transform output obtained in a 25 km fibre with strong mode coupling is shown in Figure 27.



T1524670-96

Figure 27/G.650 – PMD using Fourier analysis

2.7.2.4.2.6 PMD calculation for mixed coupling fibre systems

There may be instances where both weakly coupled fibre/components and strongly coupled fibre(s) are concatenated to form the system under test. In this case, both centroid determination (2.7.2.4.2.4) and the second moment derivation (2.7.2.4.2.5) may be required. Note that spikes in $P(\delta\tau)$ may only be determined beyond the $\delta\tau_{\text{last}}$ computed.

2.7.2.4.2.7 Spectral range

For strongly coupled fibres, sufficient spectral range must be used to form the spectral ensemble (average) with sufficient precision. The statistical uncertainty may be minimized by using the widest possible spectral range (e.g. at least 200 nm). The precision required and therefore spectral range must be specified prior to the measurement. The maximum usable range is limited by the fibre cut-off wavelength (1270 nm or below) at the short (λ_1) end, and by the detector responsivity roll-off at the high (λ_2) end (e.g. 1700 nm).

In addition, very low $\delta\tau$ values will give very long periods in $R(\lambda)$, and the spectral range λ_1 to λ_2 must cover at least two complete "cycles". The spectral range covered defines the smallest $\delta\tau$ value that can be resolved in $P(\delta\tau)$, $\delta\tau_{\text{min}}$:

$$\delta\tau_{\text{min}} = \frac{2\lambda_1\lambda_2}{(\lambda_2 - \lambda_1)c} \quad (2-35)$$

where the factor 2 is introduced to allow for the fact that two data points in P at and adjacent to zero are generally ignored (see 2.7.2.4.2.3). For example, for $\lambda_1 = 1270$ nm, $\lambda_2 = 1700$ nm, $\delta\tau_{\text{min}} = 0.033$ ps.

For weakly coupled high PMD fibres with ratio data $R(\lambda)$ resembling Figure 26 a), the requirement for spectral averaging described above may be relaxed, and the spectral range reduced [e.g. $(\lambda_2 - \lambda_1) \sim 30$ nm] in order to allow variation of PMD with wavelength to be examined.

2.7.2.4.2.8 Wavelength step size and spectral resolution

To ensure that all features (frequencies) in $R(\lambda)$ are adequately resolved, the monochromator step size, expressed in the optical frequency domain ($\Delta\nu$) must be a factor of two smaller than the "oscillation frequency" corresponding to the maximum $\delta\tau$ measured (Nyquist condition):

$$\delta\tau_{\max} = 1 / (2 \cdot \Delta\nu) \quad (2-36)$$

If from the Fourier transform, it is evident that significant energy is present near to $\delta\tau_{\max}$ [i.e. that $R(\lambda)$ appears to be "aliased"], it will be necessary to reduce the step size $\Delta\nu$ (if possible) and repeat the measurement.

The monochromator spectral linewidth (resolution) expressed in optical frequency units is generally equal to or smaller than the smallest $\Delta\nu$ value to be used (corresponding to the largest $\delta\tau$ value to be measured).

For example, for $\delta\tau_{\max} = 1.34$ ps, a monochromator linewidth of 3 nm at 1550 nm ($\Delta\nu = 374$ GHz) is typical.

2.7.2.5 Presentation of the results

- a) Identification of the fibre and/or cable measured.
- b) Test length.
- c) Polarization mode dispersion (typically in picoseconds). If the degree of mode coupling is known, the PMD coefficient may be given in ps/km (negligible mode coupling) or ps/km^{1/2} (strong mode coupling).
- d) The wavelength range over which the measurement was performed, and the wavelength or frequency step size.
- e) The physical configuration of the fibre or cable sample.
- f) Mode coupling type, e.g. deterministic, semi-random or random.
- g) When an average PMD has been obtained from repeated measurements of the sample, record the number of measurements performed.

2.7.3 Test method: Interferometric technique

2.7.3.1 General

This test method describes a procedure for measuring the average polarization mode dispersion of single-mode optical fibres and cables.

The measured value represents the PMD delay (see definition of PMD) over the measurement wavelength range of typically 60 to 80 nanometers in the 1310 nm or the 1550 nm window, depending on the user requirements.

The PMD is determined from the autocorrelation or cross-correlation function of the emerging electromagnetic field at one fibre end when illuminated by a broadband source at the other end. In the case of the autocorrelation type instrument, the interferogram has a central coherence peak corresponding to the autocorrelation of the optical source.

The main advantage of this method is that the measurement time is very fast and the equipment can be easily used in the field.

The dynamics and stability are provided by the well-established Fourier transform spectroscopy technique.

The fibre shall be single mode in the measured wavelength range.

2.7.3.2 Test apparatus

Different implementations are possible. The interferometer can be an air path type or a fibre type, it can be of Michelson or Mach-Zehnder type and it can be located at the source or at the detector end of the device under test. Examples are given in Figures 28, 29 and 30.

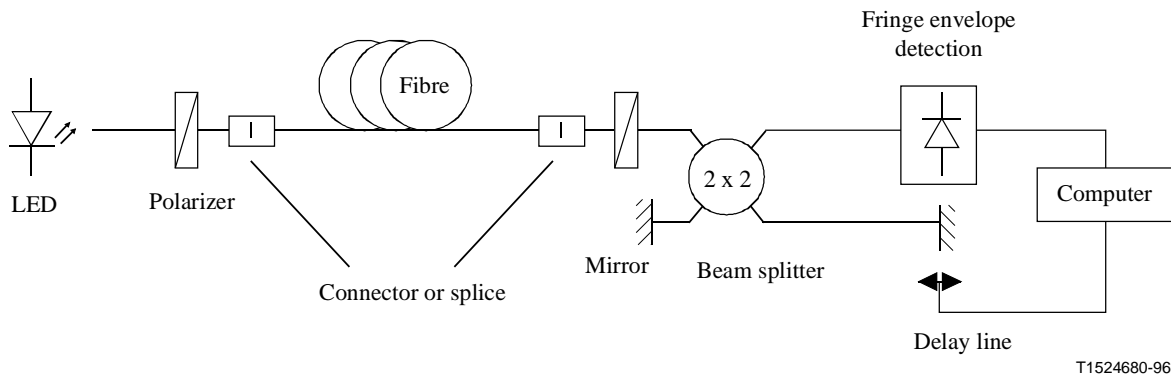


Figure 28/G.650 – The interferometric technique using Michelson interferometer with fibre coupler

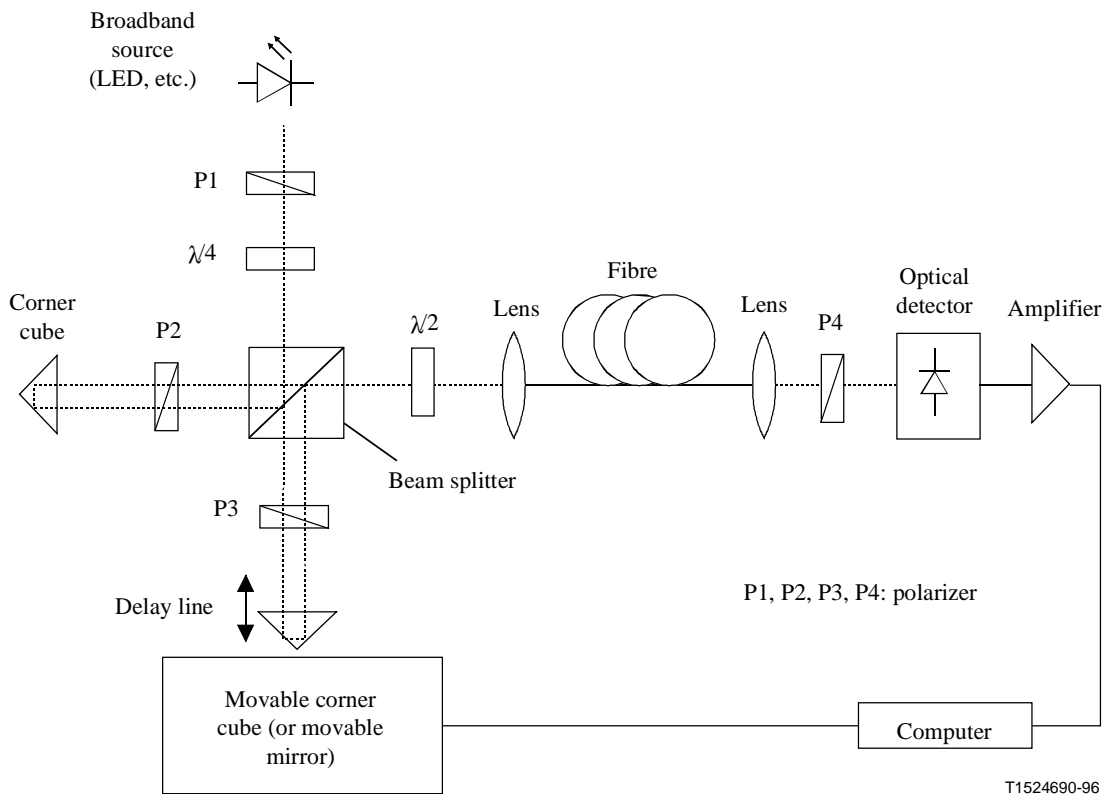
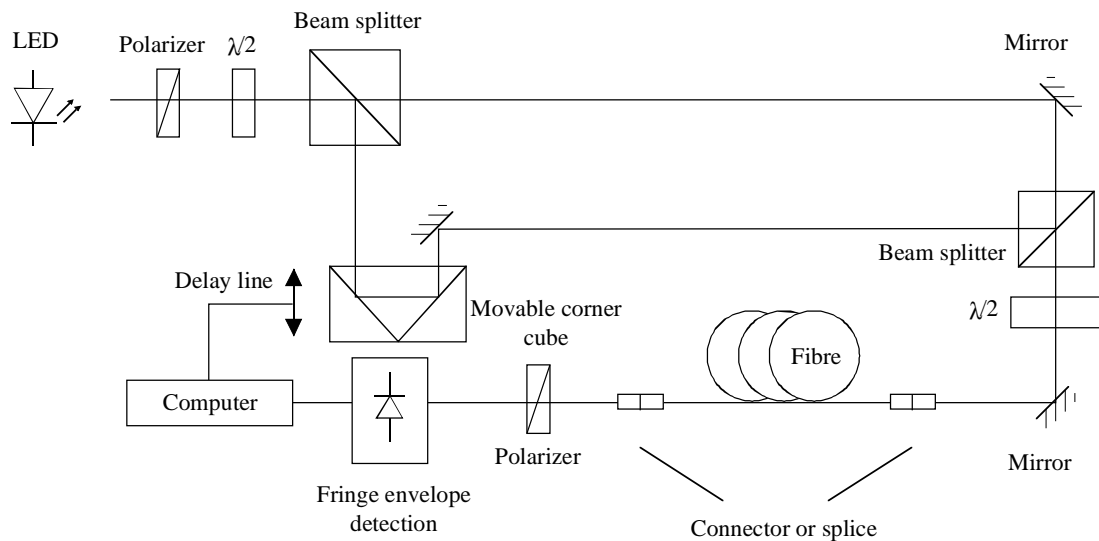


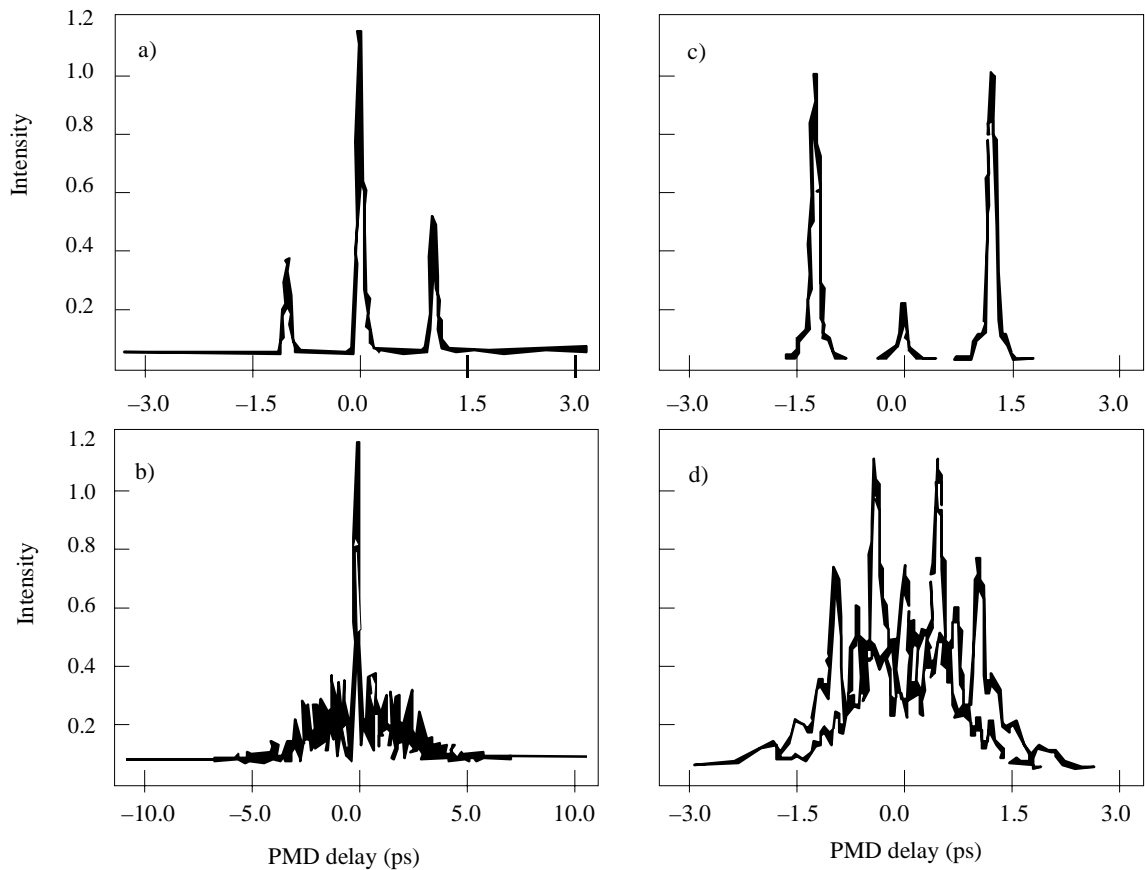
Figure 29/G.650 – The interferometric technique using a Michelson interferometer with an air path



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Figure 30/G.650 – The interferometric technique using a Mach-Zehnder type interferometer with an air path

NOTE – In an autocorrelation interferogram, there is a central autocorrelation peak when the interferometer is balanced [e.g. Figure 31 a), b)]. In contrast, cross-correlation interferograms are obtained when the polarization effects of the two arms of the interferometer are such that the central peak vanishes [e.g. Figure 31 c), d)].



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Figure 31/G.650 – Example of a fringe pattern obtained with the autocorrelation type instrument (a, b) and with the cross-correlation type instrument (c, d) for low (top) and high (bottom) polarization mode coupling

2.7.3.2.1 Optical source

A polarized broad spectrum source, such as a LED followed by a polarizer, shall be used. The central wavelength of the light source shall be within the 1310 nm and/or 1550 nm window. A typical value of its FWHM width is about 60 nm. The spectral shape shall be approximately Gaussian, without ripples which could influence the autocorrelation function of the emerging light.

2.7.3.2.2 Polarizer

The polarizer shall polarize on the full wavelength range of the source.

2.7.3.2.3 Beam splitter

The beam splitter of the interferometer is used to split the incident polarized light into two components propagating in the interferometer's arms. The splitter can be an optical coupler or a cube beam splitter.

2.7.3.2.4 Detector

The light emerging from the fibre under test is coupled to a photodetector whose signal-to-noise ratio is adequate for the measurement. The detection system may include synchronous detection by chopper/lock-in amplifier or comparable techniques.

2.7.3.2.5 Samples

The test sample shall be of known length of single-mode fibre which may or may not be cabled. The sample and pigtails must be fixed in position at nominally constant temperature throughout the measurement. The standard ambient conditions shall be employed. In the case of installed fibres and cables, prevailing deployment conditions may be used.

When it is important to minimize additional mode coupling, uncabled fibre shall be supported in some manner (usually on a reel having a minimum wind radius of 150 mm) with essentially zero fibre tension (loose winding).

Alternative fibre conditions (e.g. fibre shipping spool) may be used in case it has been demonstrated that comparable results are obtained.

NOTE – Although the test sample is normally a fibre, this test can also be performed on discrete components. In this case, PMD coefficient is not relevant.

2.7.3.2.6 Data processing

For the analysis of the interference pattern a computer with suitable software shall be used.

2.7.3.3 Measurement procedure

One end of the fibre under test is coupled to the polarized output of the polarized light source. The other end is coupled to the interferometer input shown in Figure 28 or Figure 30, or to the detector through the lens and polarizer shown in Figure 29. This can be done by standard fibre connectors, splices or by a fibre alignment system. If the latter is used some index matching oil avoids reflections.

The optical output power of the light source is adjusted to a reference value characteristic for the detection system used. To get a sufficient fringe contrast, the optical power in both arms shall be almost identical.

Make a first acquisition in moving the mirror of the interferometer arm and recording the intensity of the light. From the obtained fringe pattern for one selected state of polarization, the PMD delay can be calculated as described below. A typical example of a fringe pattern for low and high polarization mode coupling is shown in Figure 31.

In case of insufficient PM coupling or in case of low PMD, it is recommended to repeat the measurement for different polarization states or to modulate the polarization state during the measurement in order to obtain a result which is an average over all polarization states.

2.7.3.4 Determination of polarization mode dispersion

2.7.3.4.1 Weak mode coupling

In the case of weak mode coupling the PMD delay is determined from the separation of the two satellite coherence peaks, each delayed from the centre by the differential group delay of the device under test. For this case the DGD is equivalent to the PMD delay.

$$\Delta\tau = \frac{2\Delta L}{c} \quad (2-37)$$

where ΔL is the moving path of the optical delay line and c the light velocity in free space.

2.7.3.4.2 Strong mode coupling

In the case of strong mode coupling the determination of the PMD delay is based on the width of the fringe pattern interferogram. The PMD delay, $\Delta\tau$, is determined from the width parameter, σ , of the Gaussian curve fitting the interferogram according to:

$$\Delta\tau = \sqrt{\frac{3}{4}}\sigma \quad (2-38)$$

NOTE – σ is the standard deviation of the Gaussian curve.

Appendix II gives an example of an algorithm to determine the PMD delay $\Delta\tau$ from an interferogram. It can often be shown that the ratio of σ_ϵ to σ is a consistent value, which allows an alternative substitution. Other algorithms are possible, i.e. those based on cumulative integration.

For the algorithm in Appendix II, the typical measurement range is 0.1-100 ps. Other algorithms may allow this measurement range to be extended.

2.7.3.5 Equipment calibration

The equipment is calibrated by checking the mechanics of the delay line with a high birefringent fibre of known PMD delay. Another possibility is the use of a "golden fibre" with known PMD.

2.7.3.6 Presentation of the results

- a) Date.
- b) Fibre identification.
- c) Fibre type.
- d) Fibre length.
- e) Test set-up arrangement, including source type, wavelength, linewidth (FWHM).
- f) Launching technique.
- g) Type of fringe detection technique.
- h) Plot over the scanned range with fringe pattern (only if mode coupling type is not random).
- i) Fibre deployment and environmental conditions (radius, stress, temperature, etc.).
- j) Mode coupling type (random, semi-random or deterministic).
- k) PMD delay in ps and PMD coefficient. If the degree of mode coupling is known, the coefficient may be given in ps/km or ps/ $\sqrt{\text{km}}$.
- l) Other special conditions.

2.7.4 Principal state of polarization (PSP) methods

2.7.4.1 General

This method is restricted to the wavelength region of actual single-mode operation of the fibre. It can be applied to both short and long fibres, regardless of the degree of polarization mode coupling.

The method is based on the fact that when the optical frequency of the launched light is varied, the polarization state at the output of the fibre, represented on the Poincaré sphere in the space of the Stokes parameters, rotates around the axis coinciding with the direction of the PSPs at a rate dependent on the PMD delay: the greater the delay, the faster the rotation. Therefore by measuring the rotation angle $\Delta\theta$ of the representative point on the Poincaré sphere corresponding to angular frequency variation $\Delta\omega$ the PMD delay, $\delta\tau$, is obtained as:

$$\delta\tau = \left| \frac{\Delta\theta}{\Delta\omega} \right| \quad (2-39)$$

It should be noted that when one of the input PSPs is excited, the corresponding SOP at the fibre output remains unchanged by definition and no rotation is detected on the Poincaré sphere.

The technique provides directly the Differential Group Delays (DGDs) between the principal states of polarization of the fibre under test as a function of wavelength or time. The PMD is obtained by suitable averaging over time or wavelength or both. The method is able to give complete information about the statistics of the DGDs.

2.7.4.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure 32. The technique involves measuring the output state of polarization of the fibre under test at a number of wavelengths across a given spectral range by launching in the fibre under test light with fixed state of polarization.

2.7.4.2.1 Optical source

A stable single-line laser, tunable across the measurement wavelength range, is required. The spectral width of the laser must be narrow enough to ensure that depolarization of the signal due to the PMD of the fibre under test does not occur.

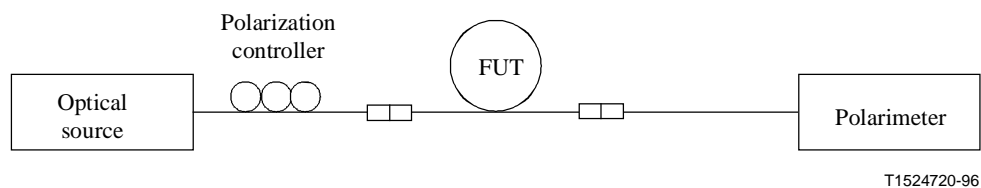


Figure 32/G.650 – Schematic of the apparatus for PMD measurement by state of polarization analysis

2.7.4.2.2 Polarization controller

A polarization controller shall be placed between the optical source and the fibre under test.

2.7.4.2.3 Polarimeter

A polarimeter to measure the Stokes parameters as a function of wavelength at the output of the fibre under test shall be used.

2.7.4.2.4 Samples

The test sample shall be of known length of single-mode fibre which may or may not be cabled. The sample and pigtails must be fixed in position at nominally constant temperature throughout the measurement. The standard ambient conditions shall be employed. In the case of installed fibres and cables, prevailing deployment conditions may be used.

When it is important to minimize additional mode coupling, uncabled fibre shall be supported in some manner (usually on a reel having a minimum wind radius of 150 mm) with essentially zero fibre tension (loose winding).

Alternative fibre conditions (e.g. fibre shipping spool) may be used in case it has been demonstrated that comparable results are obtained.

NOTE – Although the test sample is normally a fibre, this test can also be performed on discrete components. In this case, PMD coefficient is not relevant.

2.7.4.3 Measurement procedure

2.7.4.3.1 Measurement

- a) The light exiting the optical source is passed through the polarization controller and coupled to the fibre under test. The polarization controller is set so as to optimize the conditions for the determination of the rotation angle on the Poincaré sphere, if necessary. If the paths are in fibre, provide that the fibres are stationary during the measurements to follow.
- b) The output of the fibre under test is coupled to the input of the polarimeter.
- c) Select the wavelength range over which the measurement is to be performed.
- d) Select the wavelength step $\Delta\lambda$ (in nm) at which Stokes parameters are to be measured. To avoid that the output state of polarization (PSP) rotates more than 180° about the PSPs axis on the Poincaré sphere from one test wavelength to the next, the requirement $\Delta\tau_{\max} \Delta\lambda \leq 4$ ps.nm should be fulfilled, where $\Delta\tau_{\max}$ (in ps) is the maximum expected DGD of the fibre under test.
- e) The measured values of the Stokes parameters at the selected wavelengths value are recorded in a way suitable for the analysis described in the following subclauses.

2.7.4.3.2 Poincaré Sphere (PS) method

- a) The trace on the Poincaré sphere describing the evolution of the State of Polarization (SOP) with wavelength shall be reconstructed from measured Stokes parameters (S_0 , S_1 , S_2 and S_3). S_0 , S_1 , S_2 and S_3 relate to the total optical power, the linear SOP of $\theta = 0^\circ$, the linear SOP of $\theta = 45^\circ$ and the right circular SOP, respectively. In Figure 33, (o) and (x) are SOP arcs of measured values due to PMD as a function of wavelength λ . Here, P_{a-a} is Principal States of Polarization (PSP).

The trace shall be analysed piecewise, considering wavelength intervals (which may include more than two wavelength steps) such that the assumptions ensuring the existence of well-determined PSPs hold. The local PSP axis on the Poincaré sphere and the corresponding rotation angle $\Delta\Phi$ caused by the considered wavelength variation $\Delta\lambda$ are then determined by means of simple geometrical considerations. A possible procedure could be the analysis of the trace on the Poincaré sphere by considering the measured points three by three and finding the point of intersection of the axes of the segments identified by the two pairs of points. Starting from this point, it is possible to calculate the value of $\Delta\Phi$ by means of trigonometric relationships.

The DGD or PMD $\delta\tau$ is given by:

$$\delta\tau = \frac{\Delta\Phi}{2\pi\Delta f} = \frac{\Delta\Phi\lambda_1\lambda_n}{2\pi c\Delta\lambda} \quad (2-40)$$

where $\Delta\Phi$, Δf and c are the phase difference (Stokes vector arc on the Poincaré sphere), frequency difference and light velocity in free space, respectively, and λ_1 and λ_n are the initial and final wavelength of $\Delta\lambda$, respectively.

- b) The DGD (in ps) shall be calculated as a function of wavelength. Data can also be displayed in a histogram form, by plotting the distribution of frequency of occurrence of measured DGD values.
- c) The mean value of the measured DGDs, $\langle\delta\tau\rangle_\lambda$ shall be calculated over the considered wavelength range. To increase the sample size, multiple measurements can be performed.

- d) The PMD coefficients shall be calculated by suitable normalization of the measured mean value of DGD $\langle \delta\tau \rangle_\lambda$ to the length L (in km) of the fibre under test, typically square root kilometre units.

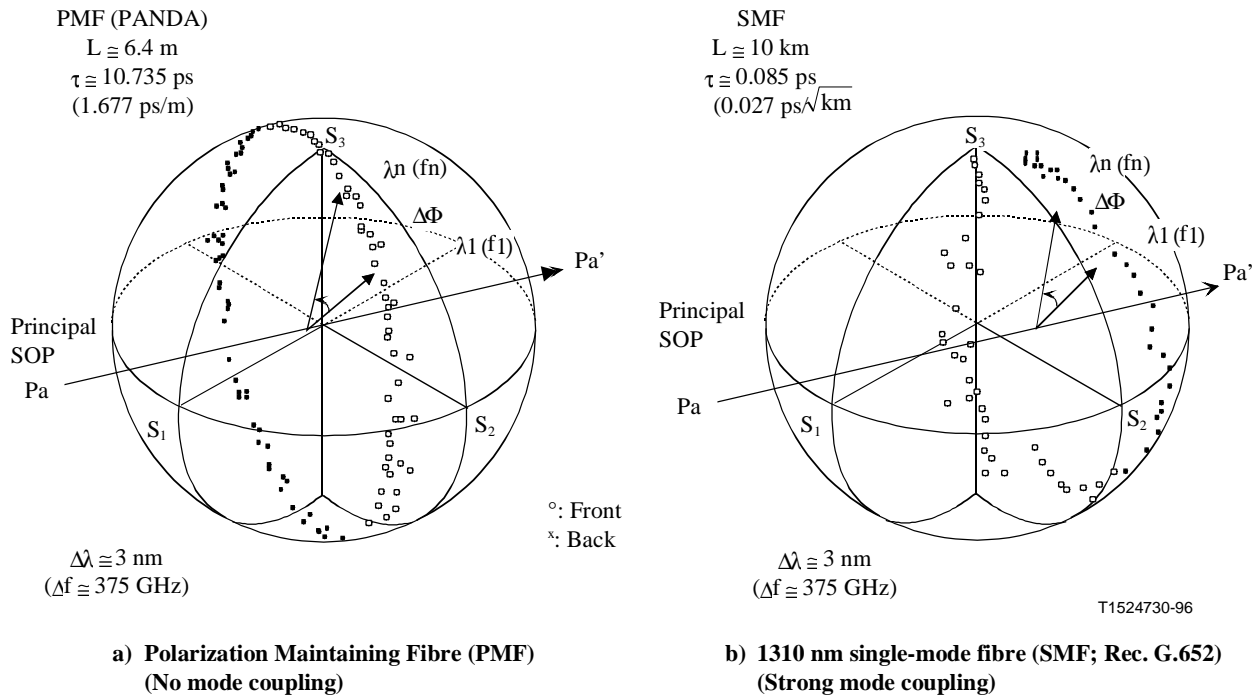


Figure 33/G.650 – Poincaré sphere representation of two examples of PMD measurements

2.7.4.3.3 State of Polarization (SOP) method

After the polarization fluctuation was measured by Stokes analyser (or rotatable analyser), it can be transformed into the SOP curve as a function of wavelength (frequency).

The SOP is expressed as:

$$SOP = \frac{1 - \eta^2}{1 + \eta^2} \quad (2-41)$$

where:

$$\eta = \tan \left[0.5 \tan^{-1} \left\{ S_3 / \sqrt{S_1^2 + S_2^2} \right\} \right] \quad (2-42)$$

Here, η is the polarization ellipticity, S_1 , S_2 and S_3 are Stokes parameters.

In Figure 34, the peak (or extrema) to peak of SOP curves is equivalent to the phase difference of π .

The DGD or PMD $\delta\tau$ is given by:

$$\delta\tau = \frac{N}{2} \cdot \frac{1}{\Delta f} = \frac{N}{2} \cdot \frac{\lambda_1 \lambda_n}{c \Delta\lambda} \quad (2-43)$$

where N represents the numbers from extrema to extrema of SOP curves.

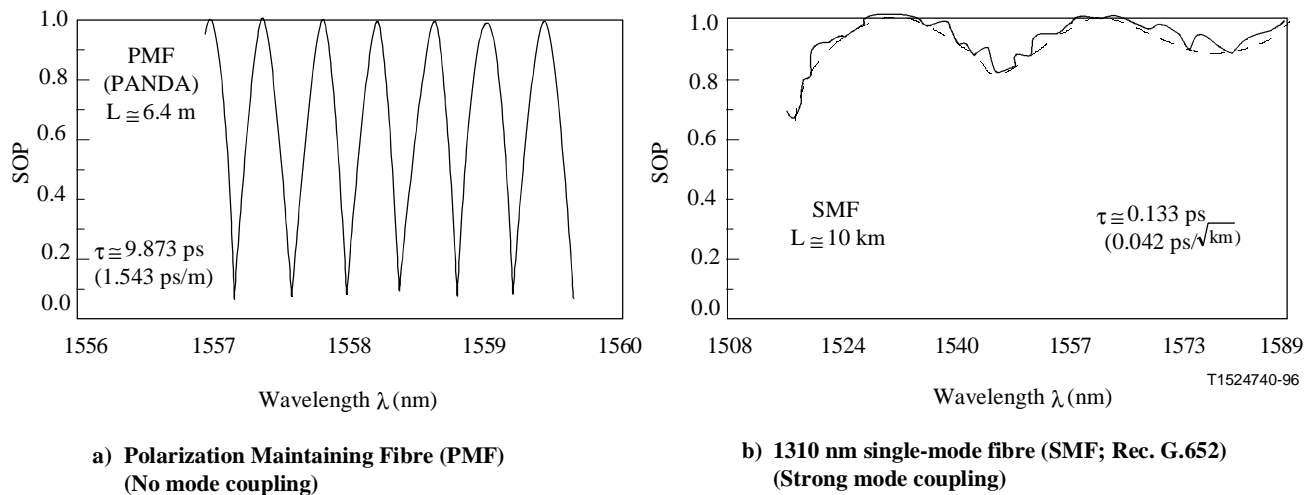


Figure 34/G.650 – State of Polarization (SOP) representation of two examples of PMD measurements

2.7.4.4 Presentation of the results

- a) Test set-up arrangement, processing algorithms.
- b) Wavelength range, wavelength step, number of sampled points.
- c) Temperature of the sample and environmental conditions.
- d) Fibre identification and length.
- e) Fibre deployment conditions.
- f) Indication of the accuracy and repeatability.
- g) Plot of the accuracy and repeatability.
- h) Histogram of the measured DGDs versus wavelength (if required).
- i) Mean DGD.
- j) PMD coefficient.

APPENDIX I

Methods of cut-off wavelength interpolation

This Appendix presents methods of determining the coefficients, A_t and B_t found in 2.3.1.3.4, equation 2-10.

I.1 Limited negative error method

The algorithm is derived from the observation that the transition structures (humps) consist of data points with a positive deviation from the expected ideal curve. The interpolation procedure is based on a theoretical model of the LP_{11} transition region and a method of fitting the data to the model. The procedure has six steps.

The first two steps define the LP_{01} region, or upper wavelength region. The second two steps define the transition region, where LP_{11} attenuation begins to increase. The fifth step characterizes this region according to a theoretical model. The last step computes the cut-off wavelength, λ_c , from the characterization parameters.

Step 1 – Define the upper wavelength region

Lower wavelength of the region

For multimode reference:

Find the maximum slope wavelength, the wavelength at which the first difference $a(\lambda) - a(\lambda + 0.01)$, is largest. For wavelengths greater than the maximum slope wavelength, the lower wavelength of the region is the wavelength at which the attenuation is minimum.

For bend reference, the following simulates the procedure for multimode reference:

Find the maximum attenuation wavelength. For wavelengths greater than the maximum attenuation wavelength, the lower wavelength of the region is the wavelength at which the following function is minimum:

$$a(\lambda) - 8 + 8\lambda \quad (\lambda \text{ in } \mu\text{m})$$

Upper wavelength of the region

Lower wavelength of region plus $0.15 \mu\text{m}$.

Step 2 – Characterize the attenuation curve, $a(\lambda)$, of the upper wavelength region as a linear equation in wavelength, λ

$$a(\lambda) \cong A_u + B_u \lambda \quad (\text{I-1})$$

The following approaches are suggested:

Bend reference method:

Set $B_u = 0$

Set A_u = median of attenuation values in the upper wavelength region.

Multimode reference method:

Find A_u and B_u such that the sum of the absolute values of error in the upper wavelength region is minimum and such that all errors are non-negative. Find the median of the errors in the upper wavelength region and add to A_u .

Determine the most negative error of the upper wavelength region, E :

$$E = \min[a(\lambda) - A_u - B_u \lambda] \quad (\text{I-2})$$

Step 3 – Find the upper wavelength of the transition region

Starting at the upper wavelength of the upper wavelength region, from Step 1, determine the maximum wavelength at which the attenuation is 0.1 dB greater than the line found in Step 2. Set the upper wavelength of the transition region to this value plus 10 nm.

Step 4 – Find the lower wavelength of the transition region

There are various methods to determine this wavelength. The following are examples:

Let:
$$\Delta a(\lambda) = a(\lambda) - A_u - B_u(\lambda) \quad (\text{I-3})$$

- Starting with the upper wavelength of the transition region, from Step 3, find the wavelength at which $\Delta a(\lambda)$ has a local maximum and so the difference between this maximum and the next local minimum (at larger λ) is maximum.
- The largest wavelength, below the upper wavelength of the transition region, such that: $\Delta a(\lambda)$ is greater than 2 dB; and

- b1) There is a local maximum for $\Delta a(\lambda)$; or
- b2) There is a local maximum for $\Delta a(\lambda) - \Delta a(\lambda + 0.01)$.

Step 5 – Characterize the transition zone with the model and constraints on errors

The model is a linear regression of a transformation. Constraints on errors control negative regression errors so that the inverse transform of the fitted line will not produce negative attenuation errors less than E, from Step 2. Fitting the data with constraints on errors may be done with simplex linear programming methods.

Find A_t and B_t , from 2.3.1.3.4, equation 2-10, such that the sum of the absolute values of error is minimized and such that no error is less than $-v(\lambda)$, with $v(\lambda)$ given as a function of E, from Step 2:

$$w(\lambda) = 10^{\frac{\Delta a(\lambda) - E}{10}} \tag{I-4}$$

$$z(\lambda) = 10 \log \left[-\frac{10}{A} \log \left(\frac{w(\lambda) - 1}{\rho} \right) \right] \tag{I-5}$$

$$v(\lambda) = Y(\lambda) - z(\lambda) \tag{I-6}$$

Step 6 – Evaluate the slope of the transition and compute the cut-off wavelength, λ_c

If B_t is greater than some small negative value, e.g. -1 to -0.1 , reduce the upper wavelength of the transition region by 10 nm and repeat Step 5.

Otherwise, compute λ_c :

$$\lambda_c = -\frac{A_t}{B_t} \tag{I-7}$$

I.2 Least squares method

This algorithm is based on the assumption that the structure sometimes seen in the transition region is caused by an interference effect around the position of the ideal curve.

The mathematical model is the same as used in the limited negative error method.

Step 1 – As limited negative error method.

Step 2 – As limited negative error method. E in equation I-2 is not required.

Step 3 – As limited negative error method.

Step 4 – As limited negative error method.

Step 5 – Characterize the transition zone.

The model is a least squares best fit of a transformation.

Find A_t and B_t from 2.3.1.3.4, equation 2-10, such that the sum of the squares of the errors is minimized, using equations 2-7, 2-8, 2-9 and:

$$W(\lambda) = 10^{\Delta a(\lambda)/10} \tag{I-8}$$

Step 6 – As limited negative error method.

APPENDIX II

Determination of PMD delay from an interferogram

This Appendix presents a method to determine the PMD delay from an interferogram with an autocorrelation peak in the centre as shown in Figure II.1.

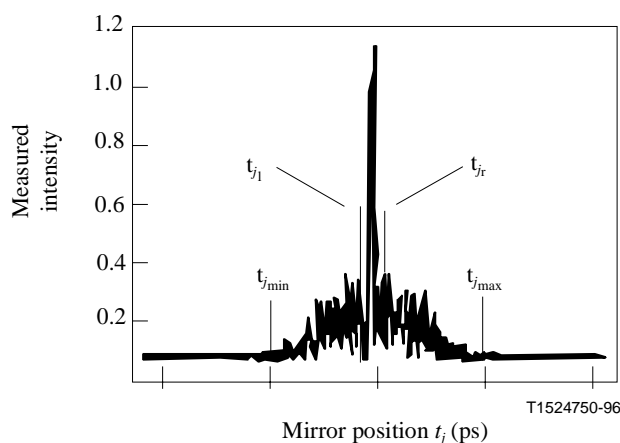


Figure II.1/G.650 – Parameters for interferogram analysis

Let \tilde{I}_j denote the measured intensity of the interferogram at increasing positions t_j , $j = 1 \dots N$, with $[t_j] = \text{ps}$.

Step 1 – Computation of the zero intensity \tilde{I}_0 and the noise amplitude Na

Definition: $N_5 = \text{round}(5N/100)$

$$\tilde{I}_0 = \frac{\sum_{j=1}^{N_5} (\tilde{I}_j + \tilde{I}_{N-j})}{2N_5} \quad (\text{II-1})$$

$$X_2 = \frac{\sum_{j=1}^{N_5} (\tilde{I}_j^2 + \tilde{I}_{N-j}^2)}{2N_5} \quad (\text{II-2})$$

$$Na = \sqrt{X_2 - I_0^2} \quad (\text{II-3})$$

Step 2 – Definition of the shifted intensity I_j

$$I_j := \tilde{I}_j - \tilde{I}_0 \quad \text{if } \tilde{I}_j - \tilde{I}_0 > 4Na \quad (\text{II-4})$$

$$I_j := 0 \quad \text{if } \tilde{I}_j - \tilde{I}_0 \leq 4Na \quad (\text{II-5})$$

Step 3 – Computation of the centre C of the interferogram

$$C = \frac{\sum_{j=1}^N t_j I_j}{\sum_{j=1}^N I_j} \quad (\text{II-6})$$

Step 4 – Removal of the central autocorrelation peak

Definition: $j_l :=$ the largest index j such that $C - t_j > \tau_c$ (II-7)

$j_r :=$ the smallest index j such that $t_j - C > \tau_c$ (II-8)

where τ_c is the source coherence time.

NOTE 1– For cross-correlation interferograms, the following definition shall be applied:

$$j_r := j_l + 1 \quad (\text{II-9})$$

Step 5 – Computation of the second moment S of the interferogram

$$S = \frac{1}{2} \left\{ \sqrt{\frac{\sum_{j=1}^{j_l} (t_j - C)^2 I_j}{\sum_{j=1}^{j_l} I_j}} + \sqrt{\frac{\sum_{j=j_r}^N (t_j - C)^2 I_j}{\sum_{j=j_r}^N I_j}} \right\} \quad (\text{II-10})$$

Step 6 – Truncate the interferogram

Set j_{\min} to the largest index j such that $C - t_j > 2S$ (II-11)

Set j_{\max} to the smallest index j such that $t_j - C > 2S$ (II-12)

Step 7 – Computation of the second moment σ_ε of the truncated interferogram

$$\sigma_\varepsilon = \frac{1}{2} \left\{ \sqrt{\frac{\sum_{j=j_{\min}}^{j_l} (t_j - C)^2 I_j}{\sum_{j=j_{\min}}^{j_l} I_j}} + \sqrt{\frac{\sum_{j=j_r}^{j_{\max}} (t_j - C)^2 I_j}{\sum_{j=j_r}^{j_{\max}} I_j}} \right\} \quad (\text{II-13})$$

Step 8 – Computation of the σ of the Gaussian $e^{-\frac{(t-C)^2}{2\sigma^2}}$ such that

$$\sigma_\varepsilon = \frac{1}{2} \left\{ \sqrt{\frac{\int_{t_{j_{\min}}}^{t_{j_l}} (t - C)^2 e^{-\frac{(t-C)^2}{2\sigma^2}} dt}{\int_{t_{j_{\min}}}^{t_{j_l}} e^{-\frac{(t-C)^2}{2\sigma^2}} dt}} + \sqrt{\frac{\int_{t_{j_r}}^{t_{j_{\max}}} (t - C)^2 e^{-\frac{(t-C)^2}{2\sigma^2}} dt}{\int_{t_{j_r}}^{t_{j_{\max}}} e^{-\frac{(t-C)^2}{2\sigma^2}} dt}} \right\} \quad (\text{II-14})$$

Step 9 – Determination of PMD delay $\Delta\tau$

$$\Delta\tau = \sqrt{\frac{3}{4}}\sigma \quad (\text{II-15})$$

NOTE 2 – For appropriately measured interferograms, it can be shown that $\frac{\sigma_\epsilon}{\sigma} \approx \sqrt{\frac{3}{4}}$.

APPENDIX III

Non-linear attributes

III.1 Background

Non-linear interactions between the signal and the silica fibre transmission medium begin to appear as optical signal powers are increased to achieve longer span lengths at high bit rates. Consequently, non-linear fibre behaviour has emerged as an important consideration both in high capacity systems and in long unregenerated routes. These non-linearities can be generally categorized as either scattering effects (stimulated Brillouin scattering and stimulated Raman scattering) or effects related to the Kerr effect, that is, the intensity dependence of the refractive index (self-phase modulation, cross-phase modulation, modulation instability, soliton formation and four wave mixing). A variety of parameters influence the severity of these non-linear effects, including fibre dispersion characteristics, the effective area of the fibre, the number of spacing of channels in multiple channel systems, overall unregenerated system length, the degree of longitudinal uniformity of the fibre characteristics, as well as signal intensity and source linewidth.

III.2 Effective area (A_{eff})

Effective area is a parameter that is closely related to optical fibre non-linearities that will affect the transmission quality of the optical fibre systems, especially in long-haul optically amplified systems.

Effective area A_{eff} is defined as follows:

$$A_{\text{eff}} = \frac{2\pi \left[\int_0^\infty I(r) r dr \right]^2}{\int_0^\infty I(r)^2 r dr} \quad (\text{III-1})$$

where $I(r)$ is the field intensity distribution of the fundamental mode of the fibre at radius r . The integration of the equation III-1 is carried out over the entire cross-sectional area of the fibre. For example, if we make a Gaussian approximation such that:

$$I(r) = \exp\left(-2r^2 / w^2\right) \quad (\text{III-2})$$

where $2w$ is the Mode Field Diameter (MFD), then equation III-1 can be analytically integrated and gives:

$$A_{\text{eff}} = \pi w^2 \quad (\text{III-3})$$

The Gaussian approximation is accurate for G.652 and G.654 step-index fibres near the LP_{11} cut-off, but for G.652 and G.654 fibres at much longer wavelengths, and in the case of G.653 dispersion shifted fibres, A_{eff} cannot be accurately estimated from equation III-3.

A more general but empirical relationship between A_{eff} and w is²:

$$A_{\text{eff}} = k\pi w^2 \quad (\text{III-4})$$

where k is a correction factor.

III.3 Correction factor k

In the experiment, the Mode Field Diameter (MFD) was measured by the variable aperture test method. From the Far-Field Pattern (FFP) of the output optical power $P(r)$, it was then possible to calculate the Near-Field Pattern (NFP) using an inverse Hankel transformation. A_{eff} is then derived from the NFP by using equation III-1.

The correction factor k in equation III-4 depends on the wavelength and on fibre parameters such as refractive index profiles, MFD and zero-dispersion wavelength. Figures III.1 and III.2 give examples of calculated and measured results for a variety of fibre types.

For other fibre designs that may be developed for optical submarine and WDM applications, the relationship of A_{eff} to w may vary, and should be determined using equation III-1. The ranges of k for these examples are summarized in Table III.1.

Table III.1/G.650 – Summary of correction factor k of A_{eff} and MFD ($= 2W$) of G.652, G.653 and G.654 fibres based on the examples in Figures III.1 and III.2

| Wavelength λ | ~ 1310 nm | ~ 1550 nm |
|-------------------------------|-----------------------------|-----------------------------|
| Fibre types | | |
| Rec. G.652 | 0.970 ~ 0.980 ^{a)} | 0.955 ~ 0.965 |
| Rec. G.654 | ... | 0.975 ~ 0.985 ^{a)} |
| Rec. G.653 | 0.940 ~ 0.950 | 0.945 ~ 0.960 ^{a)} |
| a) Optimum wavelength region. | | |

² NAMIHIRA (Y.): Relationship between non-linear effective area and mode field diameter for dispersion shifted fibres, *Electron. Lett.*, Vol. 30, No. 3, pp. 262-263, 1994.

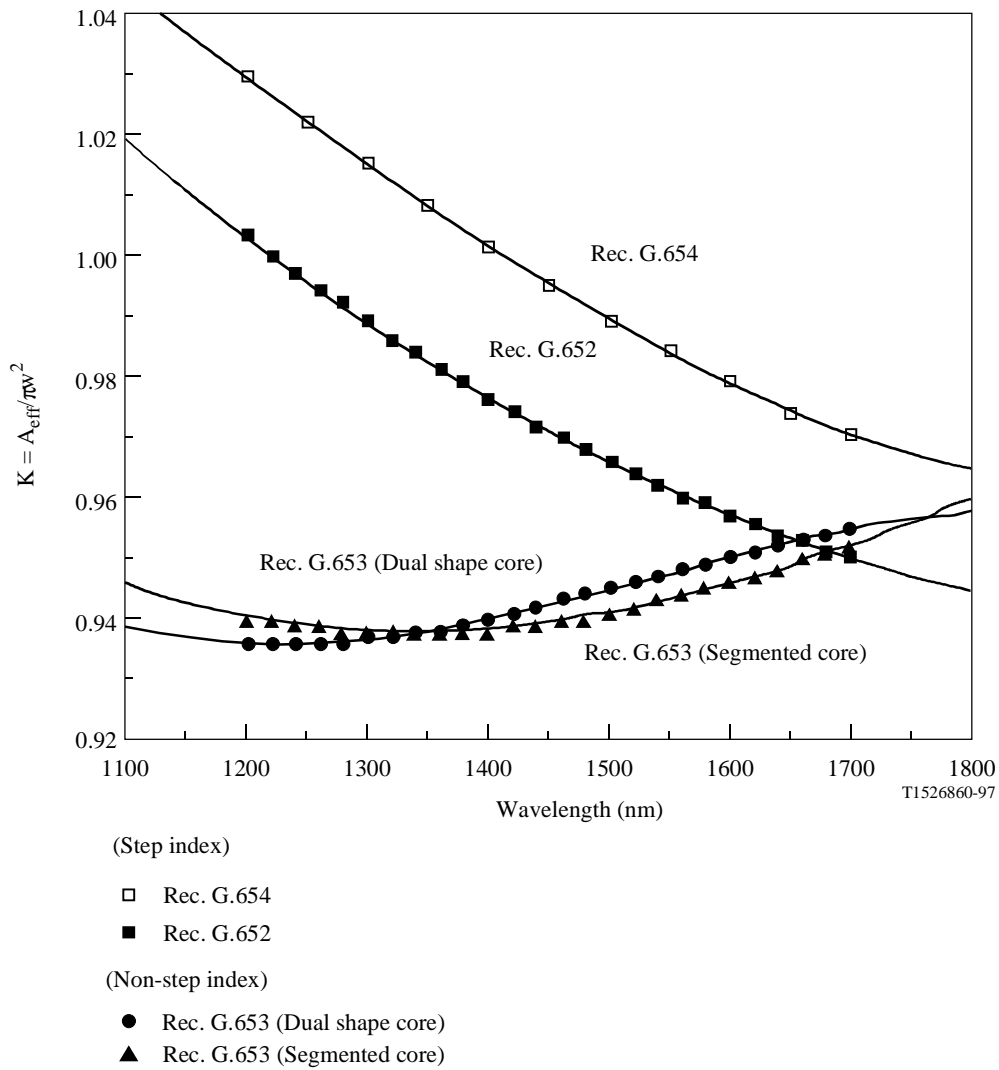


Figure III.1/G.650 – Example of calculated wavelength dependence of correction factor k of A_{eff} and MFD ($= 2W$) of G.652, G.653 and G.654 fibres

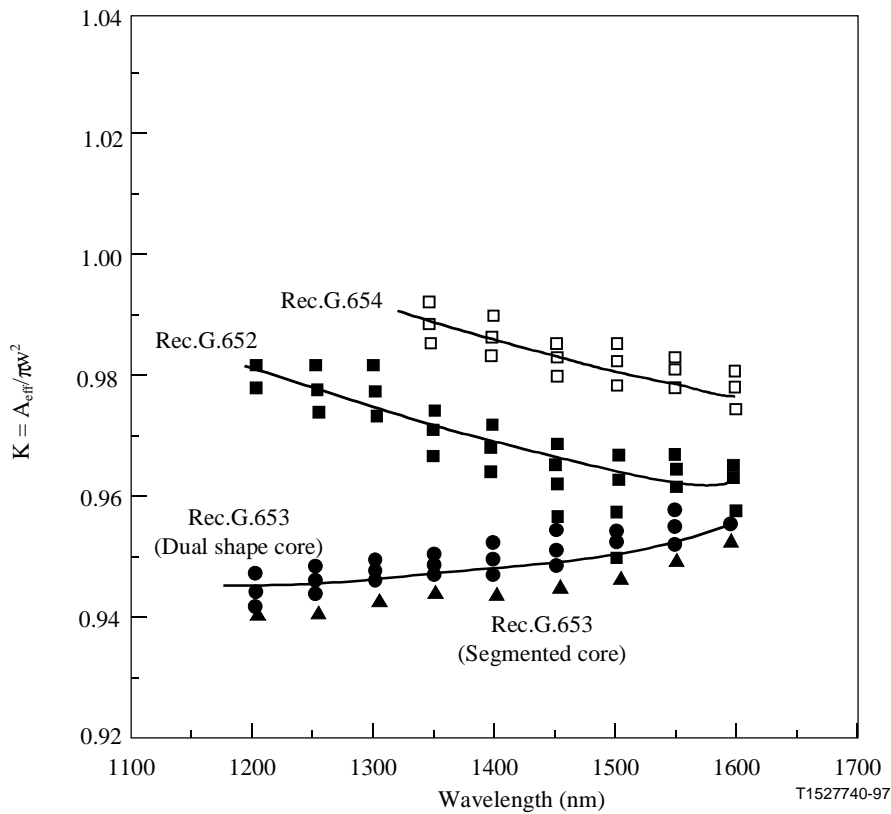


Figure III.2/G.650 – Example of measured wavelength dependence of correction factor k of A_{eff} and MFD ($= 2W$) of G.652, G.653 and G.654 fibres

III.4 Non-linear coefficient (n_2/A_{eff})

For particularly intense fields, the refractive index of optical fibres is dependent on optical intensity inside the fibres, and can be expressed as:

$$n = n_0 + n_2 I \tag{III-5}$$

where n is the refractive index, n_0 the linear part of the refractive index, n_2 the non-linear refractive index and I the optical intensity inside the fibres.

The non-linear coefficient is defined as n_2/A_{eff} . This coefficient plays an important role in evaluating the system performance degradation due to non-linearities when high power density systems are used.

Methods for measuring the non-linear coefficient are under study.

III.5 Stimulated Brillouin scattering

III.5.1 Description of the effect

In an intensity modulated system using a source with a narrow linewidth, significant optical power is transferred from the forward-propagating signal to a backward-propagating signal when the Stimulated Brillouin Scattering (SBS) threshold is exceeded. In SBS, the forward-propagating light is scattered from acoustic phonons. Phase matching (or momentum conservation) dictates that the scattered light preferentially travels in the backward direction. The scattered light is downshifted or Brillouin-shifted by approximately 11 GHz at 1550 nm.

III.5.2 SBS threshold estimation for single-mode fibres

III.5.2.1 SBS threshold

In general, the SBS threshold is expressed as:

$$P_{th} = 21 \frac{KA_{eff}}{gL_{eff}} \frac{\Delta\nu_p + \Delta\nu_B}{\Delta\nu_B} \quad (III-6)$$

where a Lorentzian pump and Brillouin linewidth is assumed, and g denotes the Brillouin gain coefficient (units of length/power) and A_{eff} the effective area. K is a constant ($1 \leq K \leq 2$) determined by the degree of freedom of the polarization state. $\Delta\nu_B$ and $\Delta\nu_p$ represent the Brillouin bandwidth and the linewidth of the pump light (MHz) respectively. L_{eff} denotes the effective length defined as:

$$L_{eff} = \frac{1 - \exp(-\alpha L)}{\alpha}, \quad (III-7)$$

where α is the attenuation coefficient and L is fibre length.

The SBS threshold, P_{th} , depends on the linewidth, $\Delta\nu_p$, of the pump light. When $\frac{\Delta\nu_p}{\Delta\nu_B} \ll 1$, P_{th} attains its minimum value, which defines the maximum steady state input power, P_m , in the absence of either a broader pump linewidth or other modulation schemes. The maximum input power can be written as:

$$P_m = 21 \frac{KA_{eff}}{gL_{eff}} \quad (III-8)$$

NOTE 1 – The actual maximum input power of a transmission system can be increased by various modulation schemes that have been reported in the literature.

NOTE 2 – Both P_{th} and P_m require an estimate of the gain coefficient, g , which must be determined experimentally and, optionally, characterized as a function of mode field diameter for a given fibre design.

III.5.2.2 Experimental set-up for SBS threshold

Figure III.3 shows a set-up to measure SBS threshold. The 1.32 μm pump is a LD pumped Nd:YAG single frequency laser with linewidth of about 5 kHz. The 1.55 μm pump is a single-mode DFB LD with a 200 kHz linewidth. The CW light from the DFB source was amplified by an Er-doped fibre amplifier. The linewidths of the pump lights are considered to be negligible compared with $\Delta\nu_B$ (20 to 100 MHz). The CW pump light is launched into the test fibre through a fibre coupler with a branching ratio of 1.9. The input, transmitted and backscattered light powers are monitored by power meters.

Figure III.4 shows an example of the transmitted and backscattered power at 1.32 μm as a function of input power for a G.654 fibre. The transmitted power stops increasing and the backscattered power rapidly increases as the input power reaches a certain power level. The SBS threshold is defined as the input pump power which produces a backscattered Stokes power equal to the transmitted pump power (see Figure III.4). Table III.2 summarizes the fibre parameters and SBS thresholds for various fibre types.

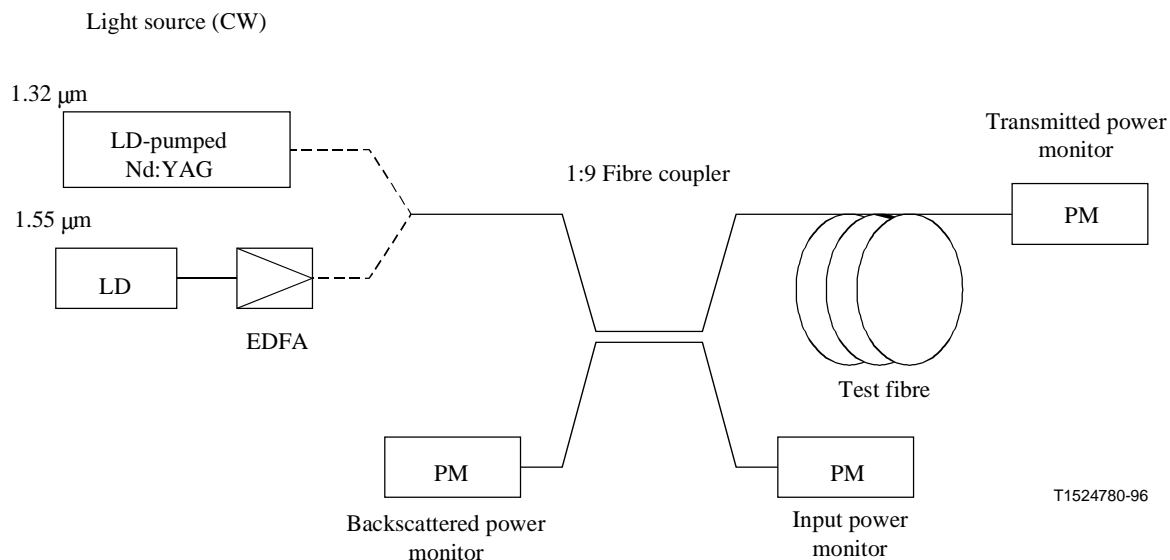


Figure III.3/G.650 – Experimental set-up

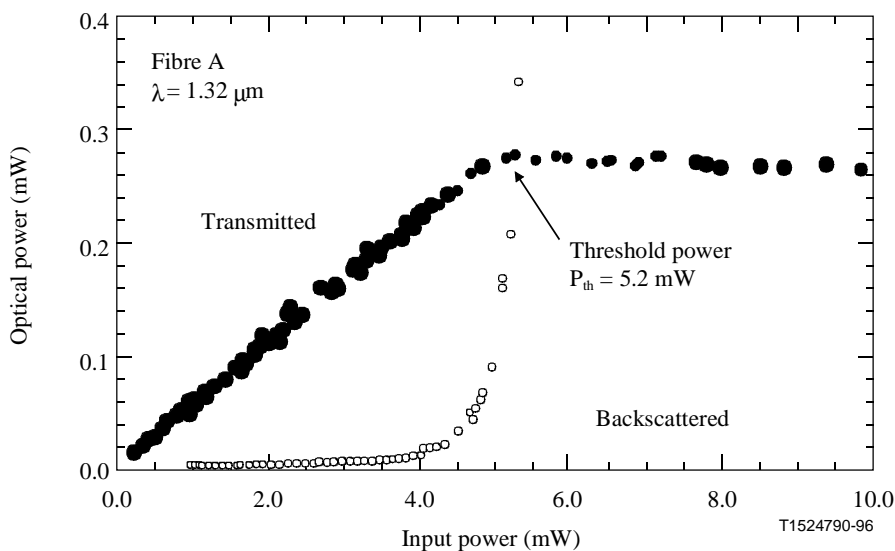


Figure III.4/G.650 – Transmitted and backscattered power as a function of input power

Threshold powers in Table III.2 are only valid for the test fibres under the described test conditions. In the normal implementation of transmission systems, significantly higher values may apply.

Table III.2/G.650 – Test fibre parameters

| Fibre | | A | B | C | D | E | F | G |
|--|---------|------------|------------|------------|------------|------------|------------|------------|
| Fibre type | | Rec. G.654 | Rec. G.652 | Rec. G.653 | Rec. G.653 | Rec. G.653 | Rec. G.653 | Rec. G.653 |
| Length L (km) | | 41.3 | 32.0 | 20.2 | 25.2 | 24.1 | 21.6 | 30.0 |
| Loss (dB/km) | 1320 nm | 0.302 | 0.322 | 0.360 | 0.360 | 0.360 | 0.362 | 0.364 |
| | 1550 nm | 0.172 | 0.194 | 0.200 | 0.200 | 0.200 | 0.200 | 0.209 |
| MFD (µm) | 1320 nm | 9.1 | 9.8 | 6.3 | 6.5 | 6.3 | 6.7 | 6.2 |
| | 1550 nm | 10.1 | 10.9 | 7.8 | 8.1 | 7.8 | 8.3 | 7.6 |
| Brillouin frequency shift change (MHz) | | 1 | 1.5 | 1.5 | --- | --- | --- | 6.0 |
| Threshold power (mW) | 1320 nm | 5.2 | 6.4 | 3.3 | 3.4 | 2.9 | 3.6 | 4.1 |
| | 1550 nm | 4.2 | 5.3 | 3.9 | 3.7 | 3.3 | 4.4 | 4.0 |

III.5.2.3 SBS threshold estimation

Figure III.5 shows the relationship between SBS threshold and A_{eff}/L_{eff} for the test fibres. This figure shows that the SBS threshold is linearly dependent on A_{eff}/L_{eff} . The SBS threshold can be estimated as the following equation:

$$P_{th} = 0.11 \left[\frac{A_{eff}}{L_{eff}} \right] \quad (III-9)$$

where A_{eff} is in μm^2 , L_{eff} in km and P_{th} in mW.

Equation III-9 can be rewritten by using fibre length L, mode field diameter 2W and attenuation coefficient α as:

$$P_{th} = 0.11 \left[k\pi \left(\frac{2W}{2} \right)^2 \frac{\alpha}{1 - \exp(-\alpha L)} \right] \quad (III-10)$$

Here, k is a correction factor that relates mode field diameter to A_{eff} for a particular fibre design and wavelength.

NOTE – If the Brillouin frequency shift changes by more than several MHz along the fibre, P_{th} will be larger than the value given by equation III-9.

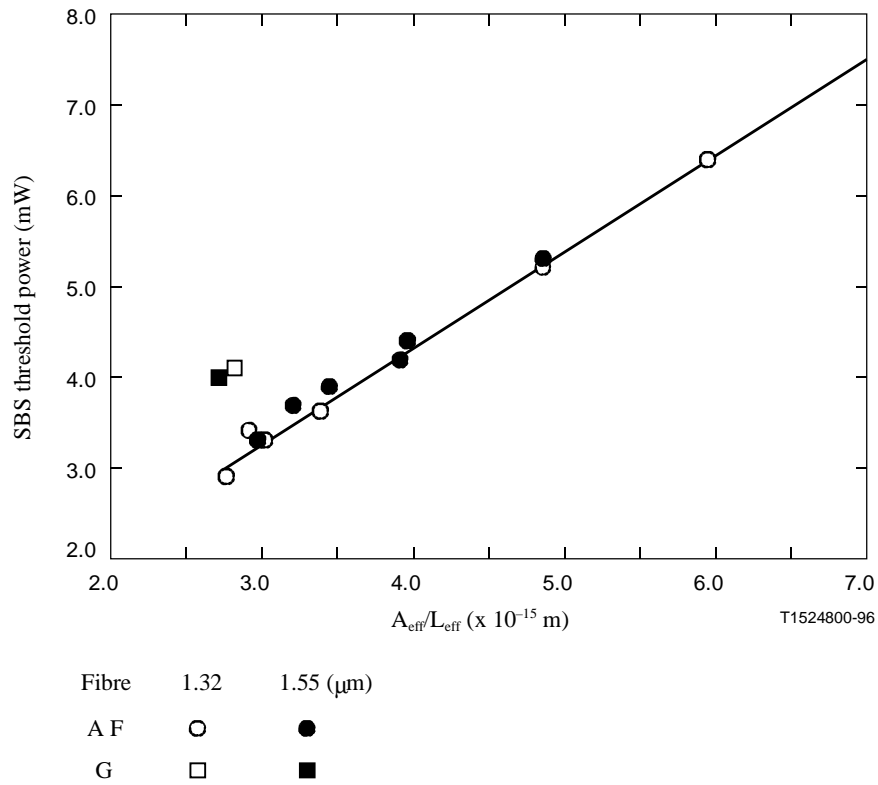


Figure III.5/G.650 – Relationship between SBS threshold and $A_{\text{eff}}/L_{\text{eff}}$

III.6 Other effects

For a description of other optical non-linear effects (four wave mixing, modulation instability, self-phase modulation, cross-phase modulation, solitons and stimulated Raman scattering), see Appendix II/G.663.

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