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

Transmission media characteristics – Optical fibre cables

Definitions and test methods for statistical and non-linear attributes of single-mode fibre and cable

ITU-T Recommendation G.650.2

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ITU-T Recommendation G.650.2

Definitions and test methods for statistical and non-linear attributes of single-mode fibre and cable

Summary

This Recommendation contains definitions of the statistical and non-linear parameters of single-mode fibre and cable. It also contains both Reference Test Methods and Alternative Test Methods for characterising these parameters.

History

1993 Definitions and test methods were removed from single-mode fibre Recommendations such as ITU-T Rec. G.652 and used to create the initial version of ITU-T Rec. G.650.

1997 The second version of ITU-T Rec. G.650 added definitions and test methods for polarization mode dispersion, and Appendices I, II, and III. The improved determination of cut-off wavelength (now 5.3.1.3.4) was also added.

2000 The third version established Reference and Alternative Test Methods for polarization mode dispersion, modified the definitions and test methods for core concentricity error (3.4 and 5.2), and added clause 5.1.4 and Appendices IV, V, and VI.

2002 In order to facilitate maintenance, ITU-T Rec. G.650 was divided into smaller Recommendations. ITU-T Rec. G.650.1 contains definitions and test methods for linear, deterministic attributes of single-mode optical fibres.

Source

ITU-T Recommendation G.650.2 was prepared by ITU-T Study Group 15 (2001-2004) and approved under the WTSA Resolution 1 procedure on 29 June 2002.

FOREWORD

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

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

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

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As of the date of approval of this Recommendation, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementors are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database.

CONTENTS

ITU-T Recommendation G.650.2

Definitions and test methods for statistical and non-linear attributes of single-mode fibre and cable

1 Scope

This Recommendation contains definitions and test methods suitable mainly for factory measurements of the statistical and non-linear attributes of the single-mode optical fibres and cables described in ITU-T Recs G.652, G.653, G.654, and G.655. These definitions and test methods are generally not appropriate for multimode fibre, such as that described in ITU-T Rec. G.651. Some of the test methods, when so indicated, may also be used to characterize discrete optical components, such as those described in ITU-T Rec. G.671. ITU-T Rec. G.650.1 contains definitions and test methods for linear deterministic attributes.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published.

2.1 Normative references

[1] ITU-T Recommendation G.652 (2000), *Characteristics of a single-mode optical fibre cable*.

[2] ITU-T Recommendation G.653 (2000), *Characteristics of a dispersion-shifted single-mode optical fibre cable*.

[3] ITU-T Recommendation G.654 (2002), *Characteristics of a cut-off shifted single-mode optical fibre cable*.

[4] ITU-T Recommendation G.655 (2000), *Characteristics of a non-zero-dispersion shifted single-mode optical fibre cable*.

[5] ITU-T Recommendation G.650.1 (2002), *Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable*.

2.2 Informative references

[6] ITU-T Recommendation G.671 (2002), *Transmission characteristics of optical components and subsystems.*

[7] ITU-T Recommendation G.663 (2000), *Application related aspects of optical amplifier devices and subsystems.*

3 Terms and definitions

3.1 Definitions

This Recommendation defines the following terms:

3.1.1 Polarization Mode Dispersion (PMD)

3.1.1.1 the phenomenon of PMD: Polarization mode dispersion is the Differential Group Delay time (DGD) between two orthogonal 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 3.1.1.2) 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.

3.1.1.2 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 depolarisation of the output field, together with an additional chromatic dispersion effect.

3.1.1.3 differential group delay ($[\delta\tau(\nu)]$ = 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 >> 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.

3.1.1.4 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:

$$P_S = 2\left(<t^2> - <t>^2\right)^{1/2} = 2\left(\frac{\int I(t)t^2 dt}{\int I(t)dt} - \left(\frac{\int I(t)t dt}{\int I(t)dt}\right)^2\right)^{1/2} \quad (3\text{-}1)$$

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 5.1.3.

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):

$$p_m = \frac{\int_{\nu_1}^{\nu_2} \delta\tau(\nu) c\nu}{\nu_2 - \nu_1} \qquad (3\text{-}2)$$

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:

$$P_r = \left(\frac{\int_{\nu_1}^{\nu_2} \delta\tau(\nu)^2 \, d\nu}{\nu_2 - \nu_1} \right)^{1/2} \qquad (3\text{-}3)$$

3.1.1.5 PMD coefficient: Two cases shall be distinguished:

– Weak mode coupling (short fibres):

$$PMD_c [ps / km] = P_s / L, P_m / L, \text{or } P_r / L \qquad (3\text{-}4)$$

– Strong mode coupling (long fibres):

$$PMD_c \left[ps/\sqrt{km}\right] = P_s/\sqrt{L},\ P_m/\sqrt{L},\ \text{or } P_r/\sqrt{L} \qquad (3\text{-}5)$$

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 (3-5).

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.

3.2 Types of test methods

3.2.1 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.

3.2.2 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.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations:

ATM	Alternative Test Method
DGD	Differential Group Delay
DWDM	Dense Wavelength Division Multiplexing
ECL	External Cavity Laser
FWHM	Full Width at Half Maximum
LD	Laser Diode
LED	Light Emitting Diode
MFD	Mode Field Diameter
NFP	Near-Field Pattern
OTDR	Optical Time Domain Reflectometer
PMD	Polarization Mode Dispersion
PS	Poincaré Sphere
PSP	Principal State of Polarization
RTM	Reference Test Method
SOP	State of Polarization
TBD	To Be Determined
WDM	Wavelength Division Multiplexing

5 Test methods

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.

5.1 Test methods for polarization mode dispersion

5.1.1 Reference test method: The Stokes parameter evaluation technique

5.1.1.1 General

This test method describes a procedure for measuring the polarization mode dispersion (PMD) of single-mode optical fibres. The change in the output state of polarization (SOP) with wavelength is determined. This change can be characterized through Jones Matrix Eigenanalysis (JME), or the rotation of the SOP vector on the Poincare Sphere (PS). 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.

For the case of strong mode coupling, a more comprehensive analysis of the Poincaré Sphere Method is under study.

When measuring fibres in motion (e.g. fibres in OPGW), the Interferometer Method could be a better choice for the dispute resolution function of the RTM.

5.1.1.2 Test apparatus

See Figure 1 for a schematic diagram of the key components in a typical measurement system.

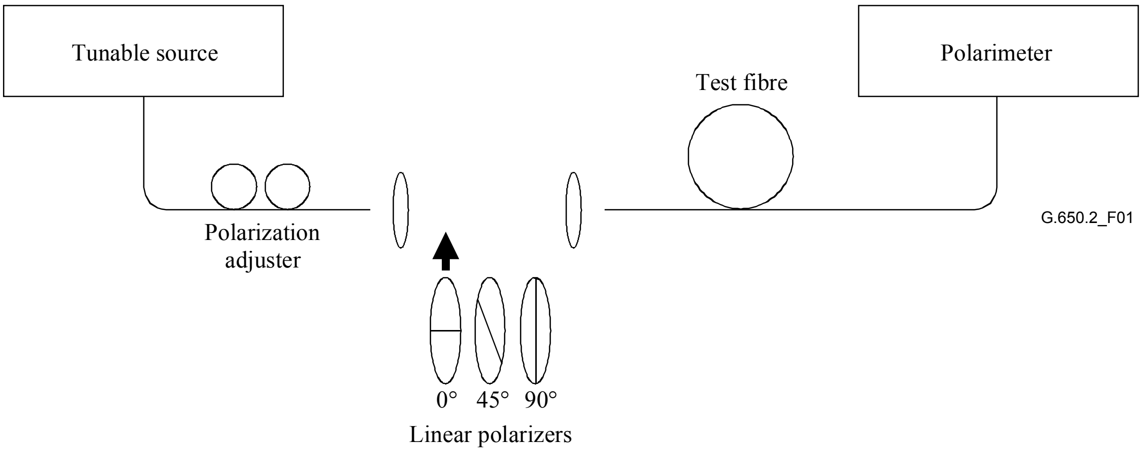


Figure 1/G.650.2 – Schematic diagram of equipment (typical)

5.1.1.2.1 Light source

Use a single-line laser or narrow-band source which is tuneable 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:

$$DOP = 100\,\mathrm{e}^{-\frac{1}{4\ln 2}\left(\frac{\pi c \Delta\tau \Delta\lambda_{FWHM}}{\lambda_0^2}\right)^2} \tag{5-1}$$

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

5.1.1.2.2 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.

5.1.1.2.3 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.

5.1.1.2.4 Input optics

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

5.1.1.2.5 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.

5.1.1.2.6 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.

5.1.1.2.7 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.

5.1.1.2.8 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.

5.1.1.2.9 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.

5.1.1.3 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 Poincaré 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 the measurements are to be performed. The maximum allowable value of $\Delta\lambda$ (around λ_0) is set by the requirement:

$$\Delta\tau_{max}\Delta\lambda \le \frac{\lambda_0^2}{2c} \tag{5-2}$$

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 Poincaré 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 vs. 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.

5.1.1.4 Calculations or interpretation of result

There are two ways (JME and PS) of analyzing the Stokes parameters that were measured in 5.1.1.3.

5.1.1.4.1 Jones Matrix Eigenanalysis

5.1.1.4.1.1 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 υ by $\omega = 2\pi\upsilon$. Find the DGD $\Delta\tau$ for the particular wavelength interval from the following expression:

$$\Delta\tau = \left| \frac{\mathrm{Arg}\left(\frac{\rho_1}{\rho_2}\right)}{\Delta\omega} \right| \tag{5-3}$$

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 $\mathrm{Arg}(\eta e^{i\theta}) = \theta$. 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.

5.1.1.4.1.2 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 2. Data may also be displayed in a histogram as shown in Figure 3.

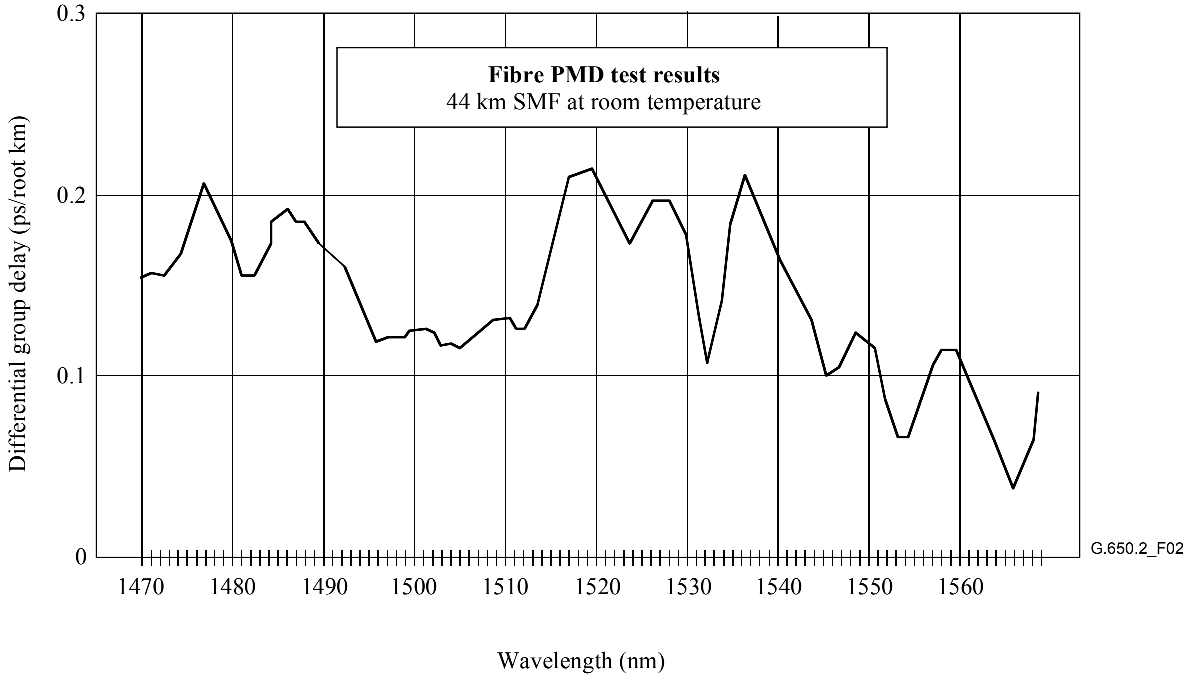
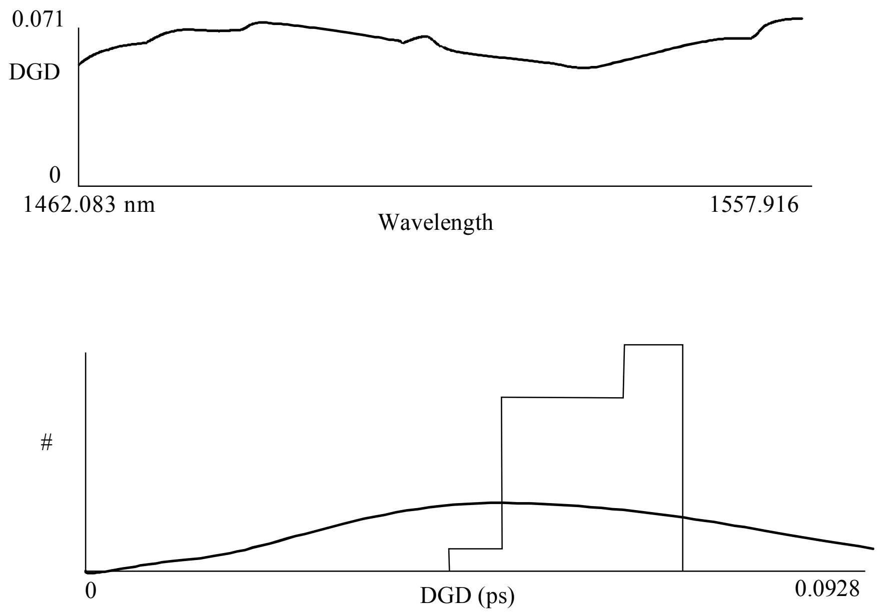
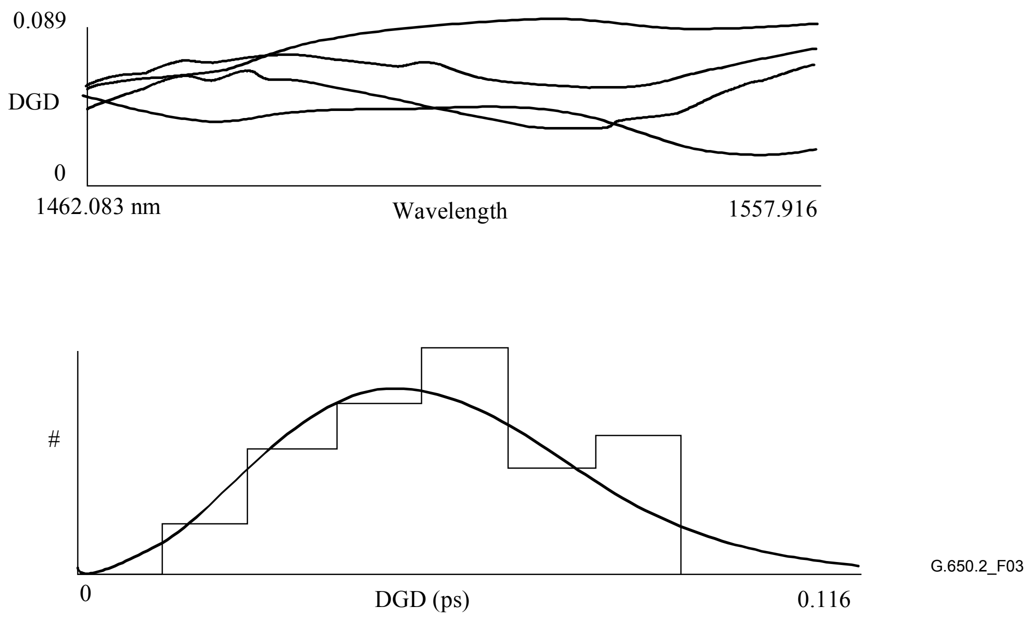


Figure 2/G.650.2 – Measured DGD of 44 km single-mode fibre



a) Single 24-interval measurement of a spooled fibre



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

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

Figure 3/G.650.2 – Examples of DGD data in histogram format

5.1.1.4.1.3 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.

5.1.1.4.1.4 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 (3-4). For fibres with random mode coupling, use the "long-length" coefficient given in Equation (3-5).

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 $<\Delta\tau>/L$.

5.1.1.4.2 Poincaré Sphere (PS) analysis

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 $\theta = 0°$, the linear SOP of $\theta = 45°$ and the right circular SOP, respectively. In Figure 4, white dots (o) and black dots (●) are SOP arcs of measured values due to PMD as a function of wavelength λ. Here, $P_{a\text{-}a}$ 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:

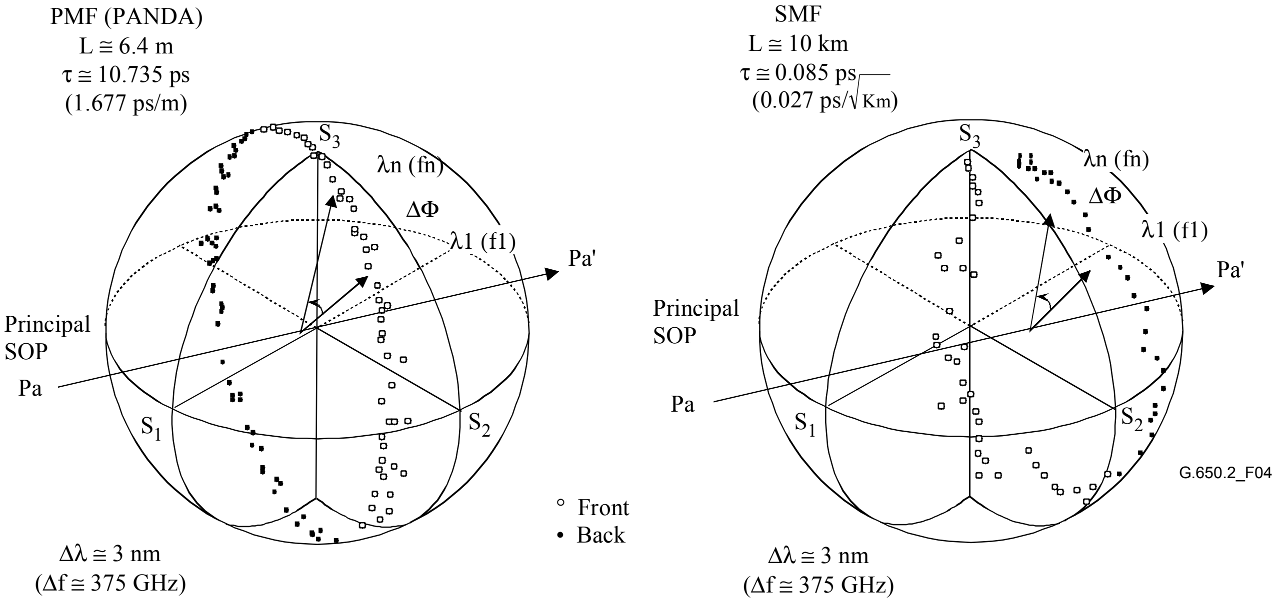
$$\delta\tau = \frac{\Delta\Phi}{2\pi\Delta f} = \frac{\Delta\Phi\lambda_1\lambda_n}{2\pi c\Delta\lambda} \tag{5-4}$$

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, $<\delta\tau>_\lambda$ 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 $<\delta\tau>_\lambda$ to the length L (in km) of the fibre under test, typically square root kilometre units.



a) Polarization Maintaining Fibre (PMF) (No mode coupling)

b) 1310 nm single-mode fibre (SMF; ITU-T Rec. G.652) (Strong mode coupling)

Figure 4/G.650.2 – Poincaré sphere representation of two examples of PMD measurements

5.1.1.5 Presentation of the results

a) Identification of the sample measured.

b) Test length.

c) The wavelength range over which the measurement was performed, the wavelength step size, and the number of sampled points.

d) The physical configuration of the fibre or cable sample.

e) Mode coupling type (negligible, semi-random, or random).

f) Method of analysis (JME or PS).

g) PMD in ps. If the degree of mode coupling is known, the PMD coefficient may be given in ps/km (negligible mode coupling), or ps/km$^{1/2}$ (random mode coupling).

h) When an average PMD has been determined from repeated measurements of the sample, record the number of measurements performed.

5.1.2 First alternative test method: State of polarization (SOP) method

5.1.2.1 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:

$$\delta\tau = \left|\frac{\Delta\theta}{\Delta\omega}\right| \qquad (5\text{-}5)$$

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.

5.1.2.2 Test apparatus

A schematic diagram of the test apparatus is shown in Figure 5. 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.

5.1.2.2.1 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.

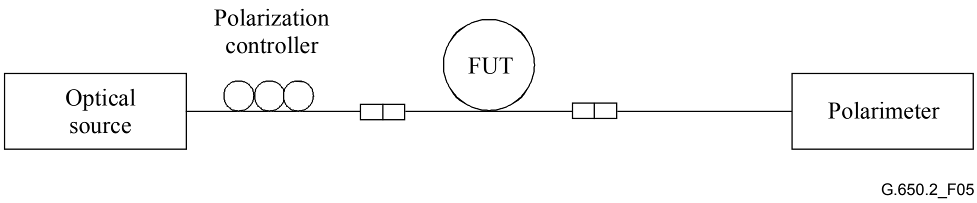


Figure 5/G.650.2 – Schematic of the apparatus for PMD measurement by state of polarization analysis

5.1.2.2.2 Polarization controller

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

5.1.2.2.3 Polarimeter

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

5.1.2.2.4 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.

5.1.2.3 Measurement procedure

5.1.2.3.1 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.

5.1.2.3.2 Calculation or interpretation of results

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

The SOP is expressed as:

$$SOP = \frac{1-\eta^2}{1+\eta^2} \tag{5-6}$$

where:

$$\eta = \tan\left[0.5\tan^{-1}\left\{S_3 / \sqrt{S_1^2 + S_2^2}\right\}\right] \tag{5-7}$$

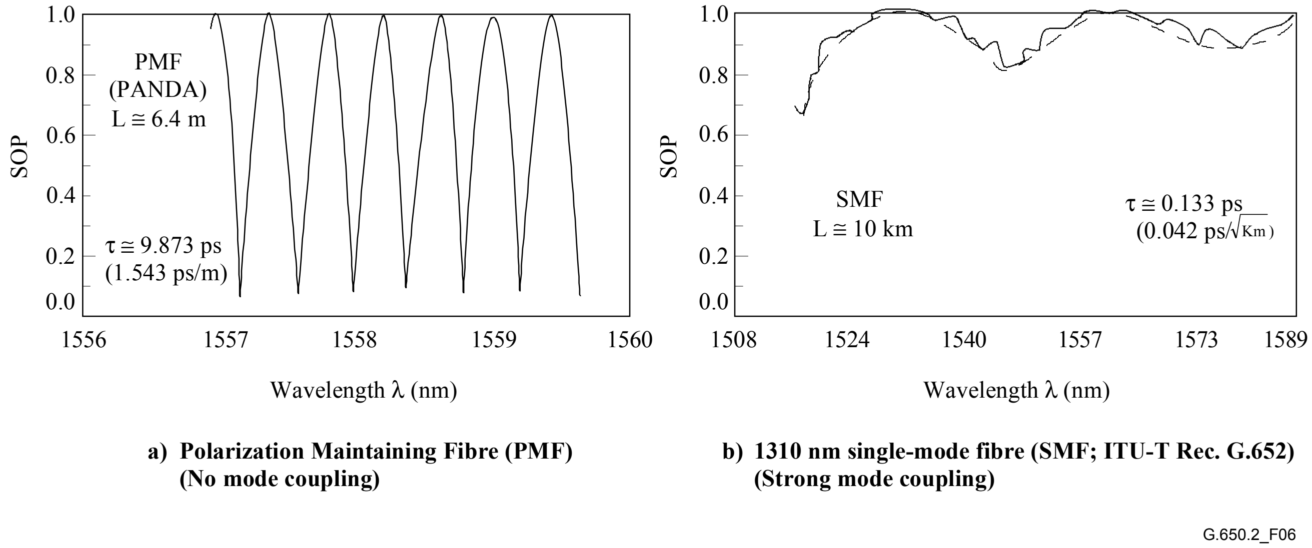
Here, η is the polarization ellipticity, S_1, S_2 and S_3 are Stokes parameters.

In Figure 6, 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:

$$\delta\tau = \frac{N}{2}\cdot\frac{1}{\Delta f} = \frac{N}{2}\cdot\frac{\lambda_1\lambda_n}{c\Delta\lambda} \tag{5-8}$$

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



a) Polarization Maintaining Fibre (PMF) (No mode coupling)

b) 1310 nm single-mode fibre (SMF; ITU-T Rec. G.652) (Strong mode coupling)

Figure 6/G.650.2 – State of Polarization (SOP) representation of two examples of PMD measurements

5.1.2.4 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.

5.1.3 Second alternative test method: Interferometric method

5.1.3.1 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.

5.1.3.2 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 7, 8 and 9.

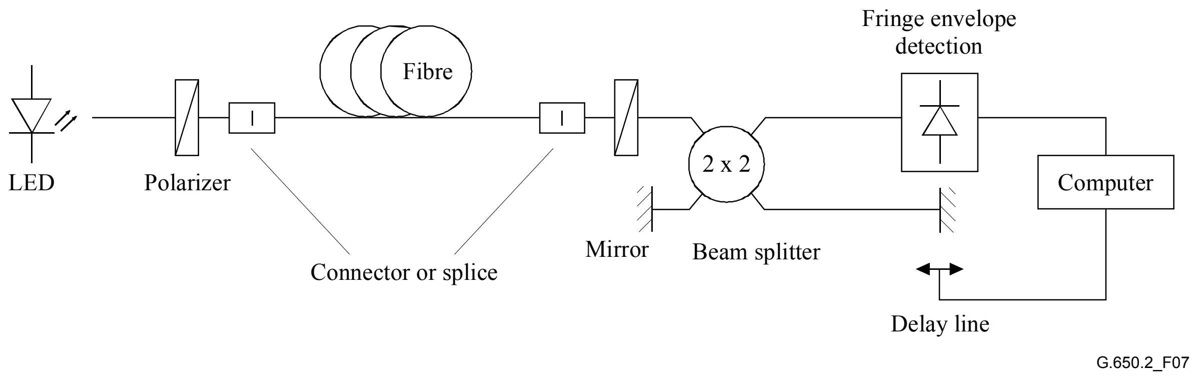


Figure 7/G.650.2 – The interferometric technique using Michelson interferometer with fibre coupler

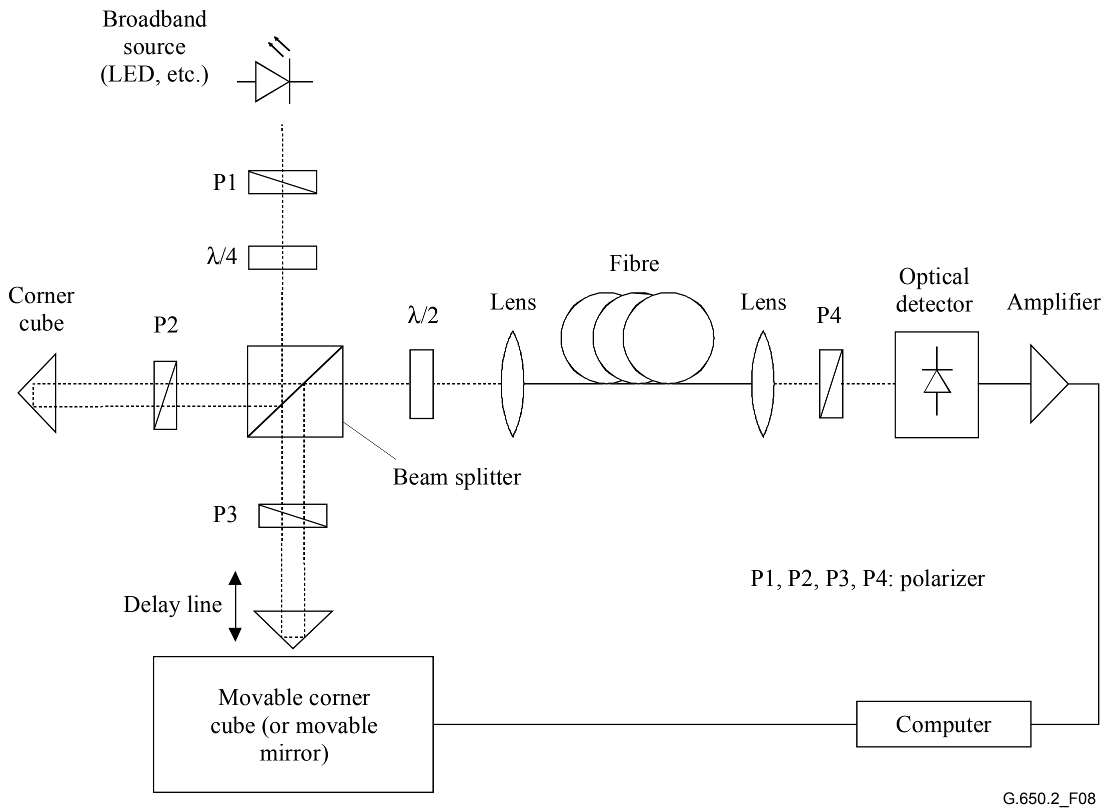


Figure 8/G.650.2 – The interferometric technique using a Michelson interferometer with an air path

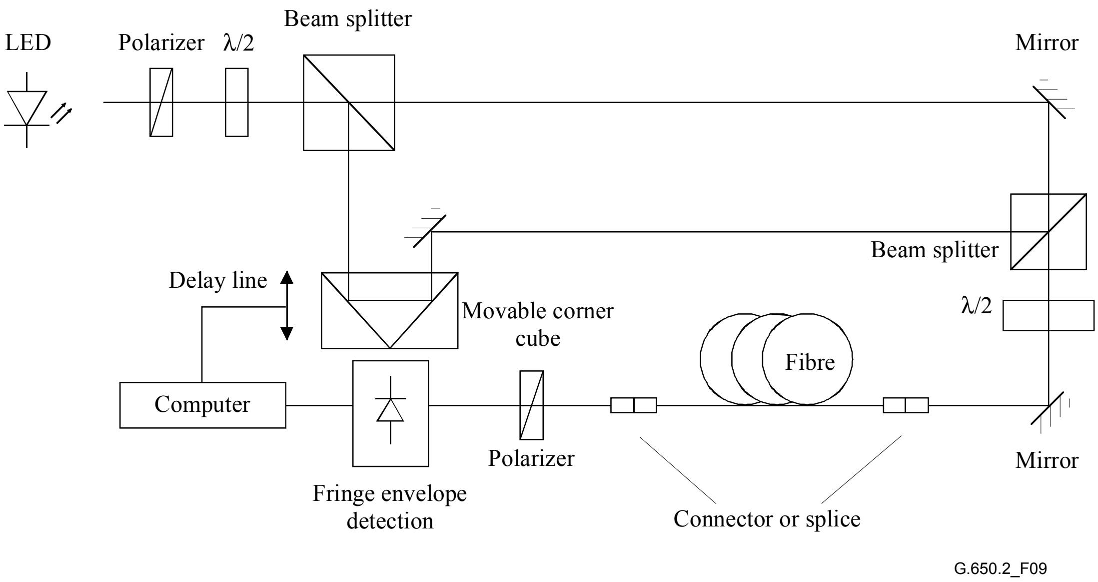


Figure 9/G.650.2 – The interferometric technique using a Mach-Zehnder type interferometer with an air path

NOTE – In an autocorrelation interferogram, there is a central autocorrelation peak when the interferometer is balanced (e.g. Figure 10 a), b)). In contrast, cross-correlation interferograms are obtained when the polarisation effects of the two arms of the interferometer are such that the central peak vanishes (e.g. Figure 10 c), d)).

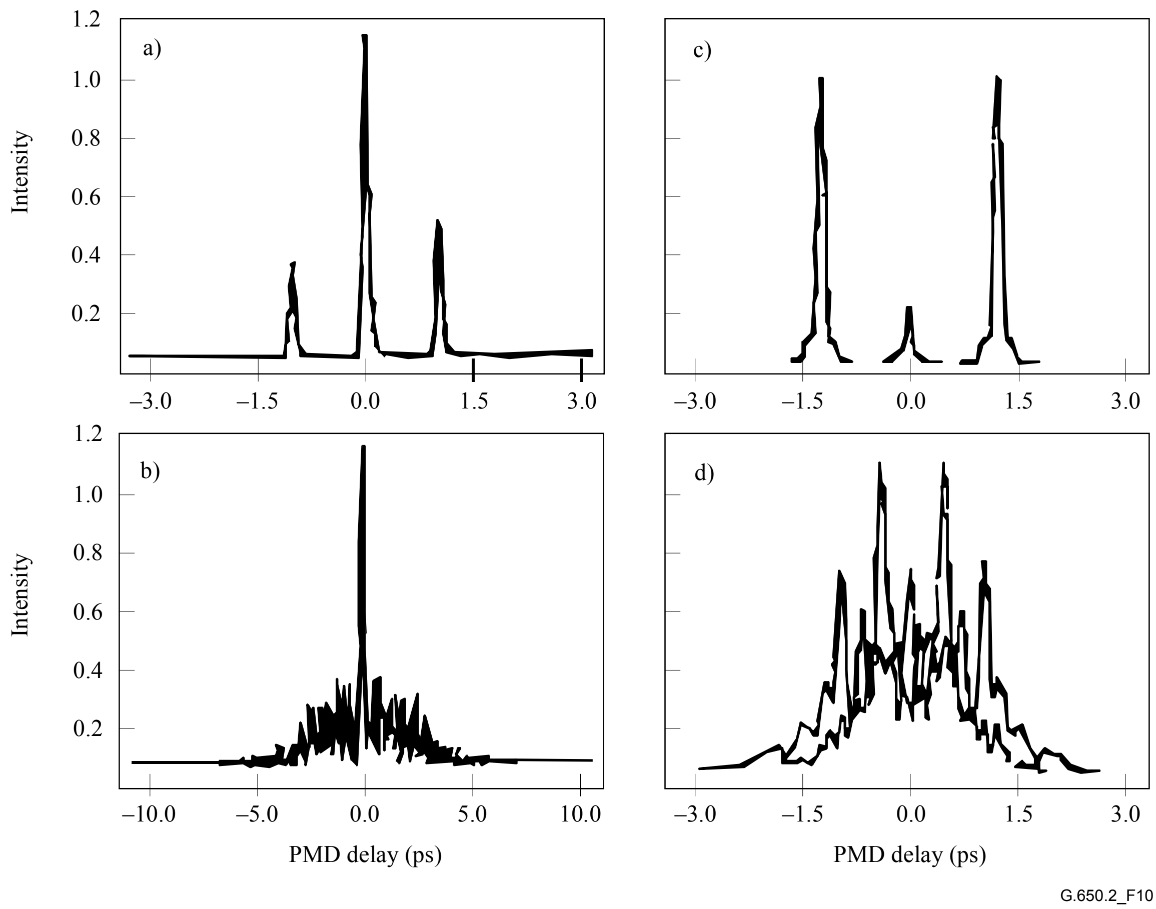


Figure 10/G.650.2 – Example of a fringe pattern obtained with the autocorrelation type instrument (a, b) and with the cross-correlation type instrument (c, d) for low (top) and high (bottom) polarization mode coupling

5.1.3.2.1 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.

5.1.3.2.2 Polarizer

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

5.1.3.2.3 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.

5.1.3.2.4 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.

5.1.3.2.5 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.

5.1.3.2.6 Data processing

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

5.1.3.3 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 7 or Figure 8, or to the detector through the lens and polarizer shown in Figure 9. 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 10.

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.

5.1.3.4 Determination of polarization mode dispersion

5.1.3.4.1 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.

$$\Delta\tau = \frac{2\Delta L}{c} \tag{5-9}$$

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

5.1.3.4.2 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:

$$\Delta\tau = \sqrt{\frac{3}{4}}\sigma \qquad (5\text{-}10)$$

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

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

5.1.3.5 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.

5.1.3.6 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.

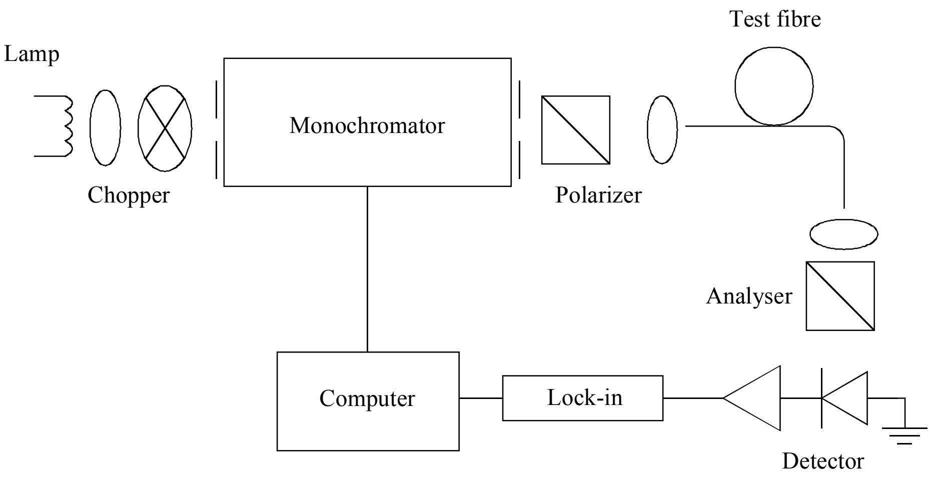
5.1.4 The fixed analyser technique

5.1.4.1 General

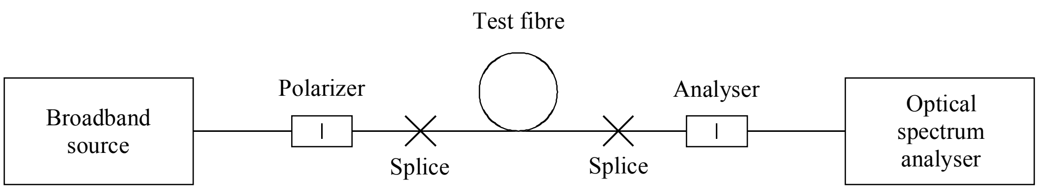
This test method describes a procedure for measuring the Polarization Mode Dispersion (PMD) of single-mode optical fibres. It produces a single measurement value that represents the PMD over the measurement wavelength range of typically a few hundred nanometers. The method can be applied to both short 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.

5.1.4.2 Test apparatus

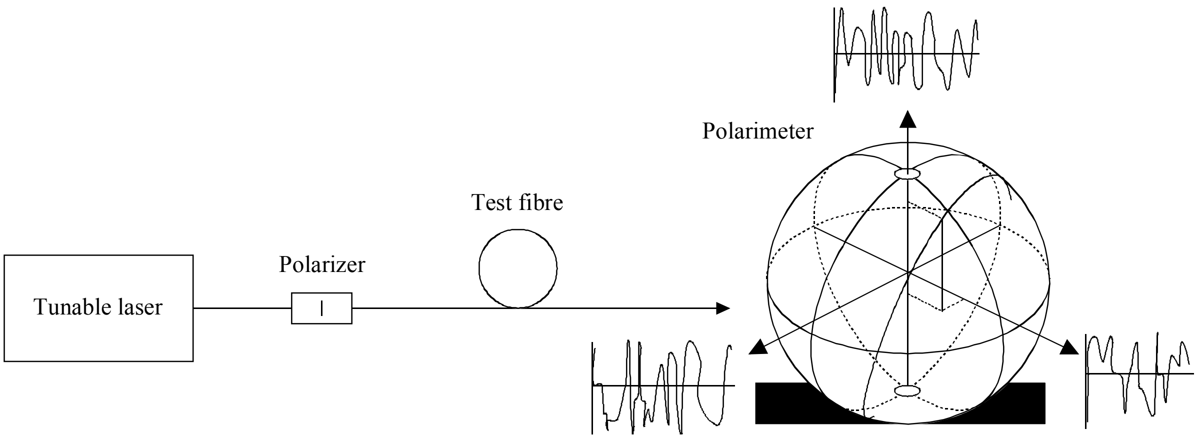
See Figure 11 for a schematic diagram of the key components in a typical measurement system.



a)



b)



c)

G.650.2_F11

Figure 11/G.650.2 – Schematic diagram of equipment (typical)

5.1.4.2.1 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.

5.1.4.2.2 Monochromator

Obtain a specified set of test wavelengths by filtering the light source with a monochromator as in Figure 11 a), or by using an optical spectrum analyzer as the detector, as in Figure 11 b). This filtering is not needed when the source is a tunable laser (see Figure 11 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 5.1.4.4.1.4 and 5.1.4.4.2.8).

5.1.4.2.3 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.

5.1.4.2.4 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.

5.1.4.2.5 Output optics

All power emitted from the test fibre must be coupled onto the active region of the detection system (see Figure 11). 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.

5.1.4.2.6 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 analyzer 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.

5.1.4.2.7 Polarizer and analyzer

The polarizer at the fibre input (Figure 11) 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 12 a). Alternatively, this may be achieved by rotation of the fibre(s) at splices or connectors.

The analyzer is not needed when a polarimeter is used for signal detection (Figure 11 c)).

5.1.4.3 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 analyzer 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 analyzer 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 5.1.4.4.1 and 5.1.4.4.2).

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 analyzer.

Remove the analyzer 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:

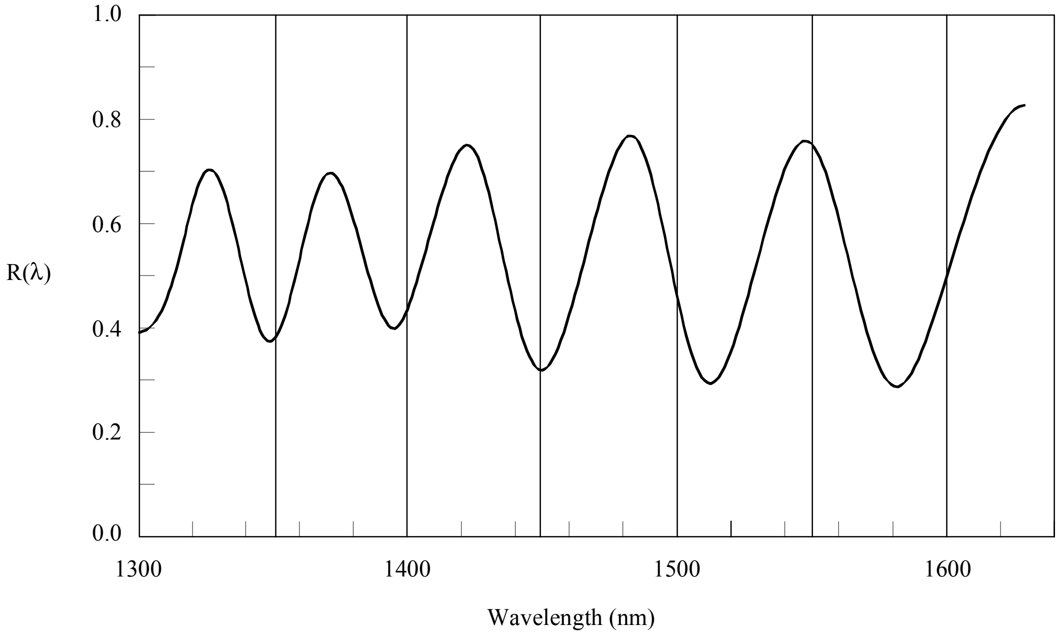
$$R(\lambda) = \frac{P_A(\lambda)}{P_{TOT}(\lambda)} \tag{5-11}$$

are shown in Figure 12.

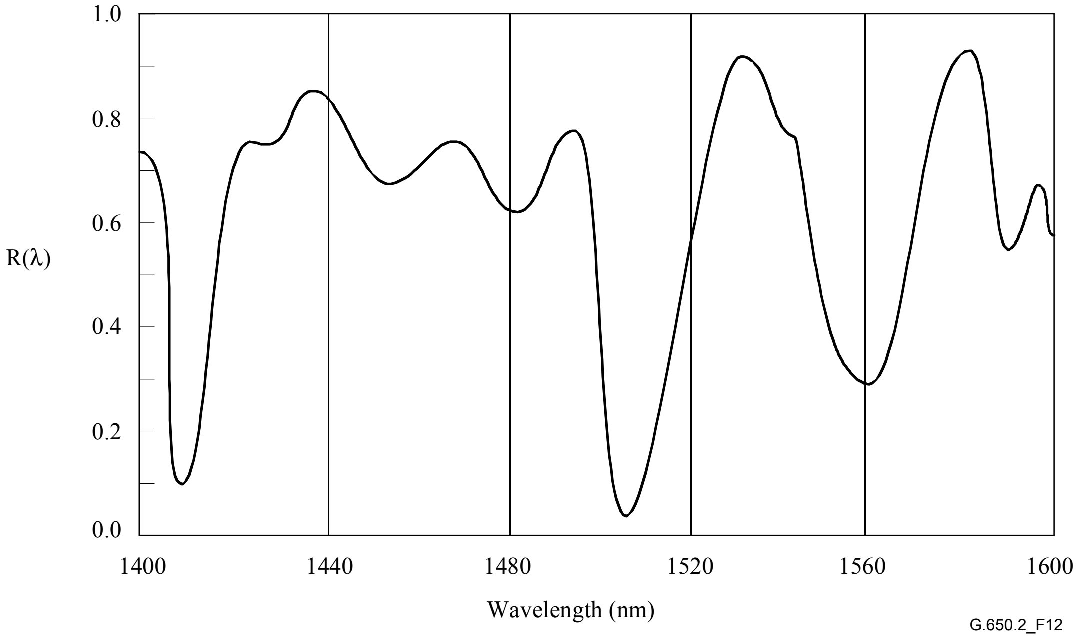
An alternative procedure is to leave the analyzer in place, but rotate it 90° with respect to the orientation used above. Calling the power received in this case $P_{ROT}(\lambda)$, then:

$$R(\lambda) = \frac{P_A(\lambda)}{P_A(\lambda) + P_{ROT}(\lambda)} \tag{5-12}$$

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 analyzed by the same methods applied to $R(\lambda)$ (see 5.1.4.4.1 and 5.1.4.4.2). Each normalized Stokes parameter then leads to a value of $\langle\Delta\tau\rangle$.



a) Weak mode coupling



b) Strong mode coupling

Figure 12/G.650.2 – Typical data obtained in measuring PMD

5.1.4.4 Calculations or interpretation of results

One of the following two methods (5.1.4.4.1 and 5.1.4.4.2) shall be used for calculating PMD from the measurement data.

5.1.4.4.1 Extrema counting

5.1.4.4.1.1 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.

$$< \Delta\tau >= \frac{k\,E\,\lambda_1\lambda_2}{2\,(\lambda_2 - \lambda_1)c} \tag{5-13}$$

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 (3-4) regime) and 0.82 in the limit of strong mode coupling (the Equation (3-5) regime).

If a polarimeter is used as the detection element, take as the final value of $<\Delta\tau>$ the average of the values derived from the three normalized Stokes parameter responses. The value of $<\Delta\tau>$ provided by Equation (5-13) or the average of the three values of $<\Delta\tau>$ derived from polarimetric detection can be used in Equation (3-4) or (3-5) (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 $\lambda_1 < \lambda < \lambda_2$.

5.1.4.4.1.2 Accuracy

The best accuracy is obtained by making $(\lambda_2 - \lambda_1)$ large enough to insure that $E >> 1$. This is especially important when there is strong mode coupling (Figure 12 b)) and less so otherwise (Figure 12 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 centered 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).

5.1.4.4.1.3 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 12 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.

5.1.4.4.1.4 Spectral resolution

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

$$\Delta\lambda / \lambda < (8\nu\Delta\tau)^{-1} \tag{5-14}$$

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 (5-14) reduces to the condition that $\Delta\lambda$ (nm) should be less than the reciprocal of $\Delta\tau$(ps).

5.1.4.4.2 Fourier analysis

5.1.4.4.2.1 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, $<\Delta\tau>$, for the fibre under test. This method is applicable to fibres with weak or strong mode coupling (refer to 5.1.4.4.2.4 and 5.1.4.4.2.5, respectively).

5.1.4.4.2.2 Data preprocessing 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 5.1.4.3) 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 (5-11) or (5-12) 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 preconditioning 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 $\delta\tau$.

5.1.4.4.2.3 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 analyzer 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* (number of original data points) / (total length of array after zero-padding). Use clause 5.1.4.4.2.4 to calculate PMD. If this is not the case, proceed to calculate PMD using clauses 5.1.4.4.2.5 or 5.1.4.4.2.6.

5.1.4.4.2.4 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 12 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 $<\Delta\tau>$.

To define the spike centroid <Δτ>, those points where P(δτ) 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:

$$< \Delta\tau >= \frac{\sum_{e=0}^{M'} \left[P_e(\delta\tau)\delta\tau_e \right]}{\sum_{e=0}^{M'} \left[P_e(\delta\tau) \right]} \tag{5-15}$$

where M' + 1 is the number of data points of P within the spike which exceed T_2. <Δτ> in Equation (5-15) is typically quoted in picoseconds. If the device under test is a fibre of length L, the PMD coefficient may be calculated using Equation (3-4). 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.

5.1.4.4.2.5 PMD calculation for fibres with strong mode coupling

In instances of strong mode coupling, R(λ) becomes a complex waveform similar to Figure 12 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(δτ) representing the autocorrelation of the probability distribution of light pulse arrival times, δτ, 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(δτ), for a strongly mode-coupled fibre, that is not substantially affected by measurement noise. The δτ value for this point is denoted $\delta\tau_{last}$, and the value of j at $\delta\tau_{last}$ 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 <Δτ>, and is given by:

$$< \Delta\tau >= \sigma_R = \left\{ \frac{\sum_{j=0}^{M''} \left[P_j(\delta\tau)\delta\tau_j^2 \right]}{\sum_{j=0}^{M''} \left[P_j(\delta\tau) \right]} \right\}^{1/2} \tag{5-16}$$

The <Δτ> value given by Equation (5-16) 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 13.

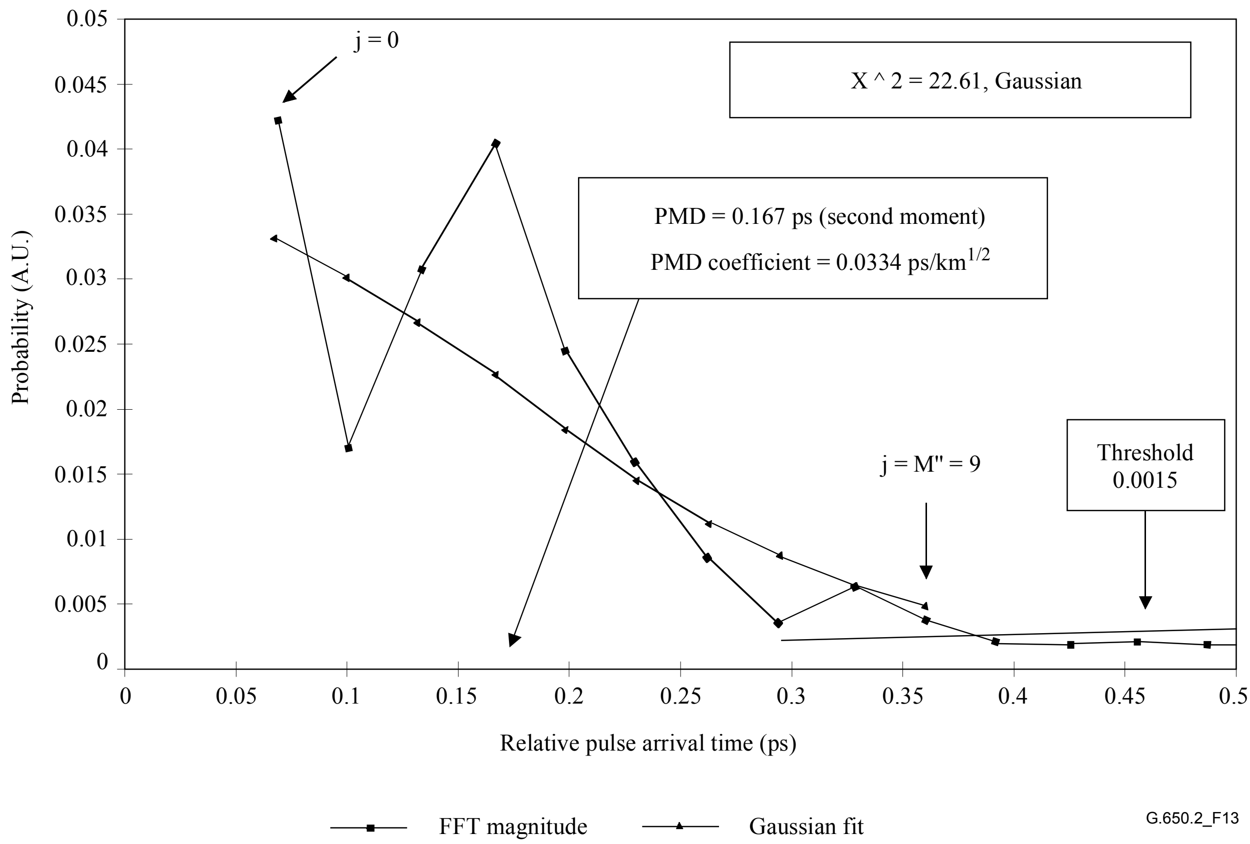


Figure 13/G.650.2 – PMD using Fourier analysis

5.1.4.4.2.6 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 (5.1.4.4.2.4) and the second moment derivation (5.1.4.4.2.5) may be required. Note that spikes in $P(\delta\tau)$ may only be determined beyond the $\delta\tau_{last}$ computed.

5.1.4.4.2.7 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 $P(\delta\tau)$, $\delta\tau_{min}$:

$$\delta\tau_{min} = \frac{2\lambda_1\lambda_2}{(\lambda_2 - \lambda_1)c} \tag{5-17}$$

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 5.1.4.4.2.3). For example, for $\lambda_1 = 1270$ nm, $\lambda_2 = 1700$ nm, $\delta\tau_{min} = 0.033$ ps.

For weakly coupled high PMD fibres with ratio data $R(\lambda)$ resembling Figure 12 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.

5.1.4.4.2.8 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):

$$\delta\tau_{max} = 1/(2 \cdot \Delta\nu) \tag{5-18}$$

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.

5.1.4.5 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.

5.2 Test methods for non-linear attributes

(Under study).

Appendix I[1]

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 I.1.

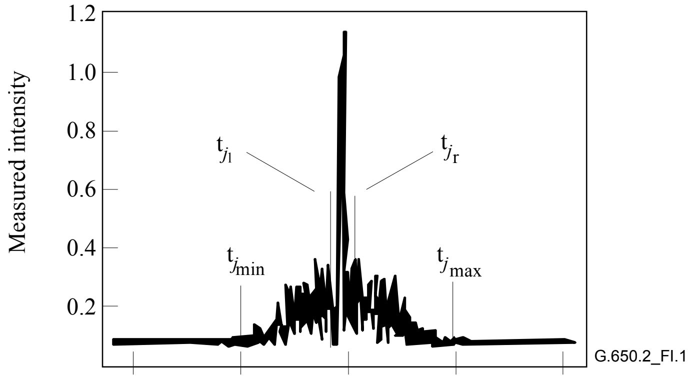


Figure I.1/G.650.2 – Parameters for interferogram analysis

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

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

Definition: N_5 = round (5 N/100)

$$\tilde{I}_0 = \frac{\sum_{j=1}^{N_5}\left(\tilde{I}_j + \tilde{I}_{N-j}\right)}{2N_5} \tag{I-1}$$

$$X_2 = \frac{\sum_{j=1}^{N_5}\left(\tilde{I}_j^2 + \tilde{I}_{N-j}^2\right)}{2N_5} \tag{I-2}$$

$$Na = \sqrt{X_2 - I_0^2} \tag{I-3}$$

Step 2 – Definition of the shifted intensity I_j

$$I_j := \tilde{I}_j - \tilde{I}_0 \text{ if } \tilde{I}_j - \tilde{I}_0 > 4Na \tag{I-4}$$

$$I_j := 0 \quad if\, \tilde{I}_j - \tilde{I}_0 \le 4Na \tag{I-5}$$

[1] This is Appendix II of ITU-T Rec. G.650 (2000)

Step 3 – Computation of the centre *C* of the interferogram

$$C = \frac{\sum_{j=1}^{N} t_j I_j}{\sum_{j=1}^{N} I_j} \tag{I-6}$$

Step 4 – Removal of the central autocorrelation peak

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

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

where τ_c is the source coherence time.

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

$$j_r := j_l + 1 \tag{I-9}$$

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

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

Step 6 – Truncate the interferogram

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

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

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

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

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

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

Step 9 – Determination of PMD delay Δτ

$$\Delta\tau = \sqrt{\frac{3}{4}}\sigma \tag{I-15}$$

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

Appendix II

Non-linear attributes

II.1 Background

Non-linear interactions between the signal and the silica fibre transmission medium begin to appear as optical signal powers and 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.

II.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:

$$A_{eff} = \frac{2\pi\left[\int_0^\infty I(r)rdr\right]}{\int_0^\infty I(r)^2 rdr} \tag{II-1}$$

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

$$I(r) = \exp\left(-2r^2 / W^2\right) \tag{II-2}$$

where 2w is the Mode Field Diameter (MFD), then Equation (II-l) can be analytically integrated and gives:

$$A_{eff} = \pi w^2 \tag{II-3}$$

The Gaussian approximation is accurate for G.652 [1] and G.654 [3] 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 [2] dispersion shifted fibres, A_{eff} cannot be accurately estimated from Equation (II-3).

A more general but empirical relationship between A_{eff} and w is[2]:

$$A_{eff} = k\pi w^2 \tag{II-4}$$

where k is a correction factor.

II.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 (II-1).

The correction factor k in Equation (II-4) depends on the wavelength and on fibre parameters such as refractive index profiles, MFD and zero-dispersion wavelength.

Figure II.1 shows examples of measured wavelength dependence of MFD and A_{eff} for G.652 and G.653 fibres in the 1200-1600 nm wavelength regions. Figure II.2 gives examples of calculated and measured wavelength dependence of MFD, A_{eff}, and the correction factor k for G.652, G.653, and G.654 fibres in this same wavelength region.

The ranges of the correction factor k for these examples are summarized in Table II.1.

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 (II-1).

Figure II.3 shows the wavelength dependence of A_{eff} for G.653 (DSF) and G.655 (NZ-DSF) fibres in the 1520-1580 nm wavelength regions for WDM applications.

The average k values and standard deviation were found to be around 0.953 $\pm$ .005 for the G.653 fibres, and 1.09 $\pm$ .070 for the G.655 fibres.

Table II.1/G.650.2 – Summary of correction factor k of A_{eff} and MFD (= 2W) for G.652, G.653 and G.654 fibres based on the examples in Figure II.2

Wavelength λ / Fibre types	~ 1310 nm	~ 1550 nm
ITU-T Rec. G.652	0.970 ~ 0.980 (Note)	0.960 ~ 0.970
ITU-T Rec. G.654	...	0.975 ~ 0.985 (Note)
ITU-T Rec. G.653	0.940 ~ 0.950	0.950 ~ 0.960 (Note)
NOTE – 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.

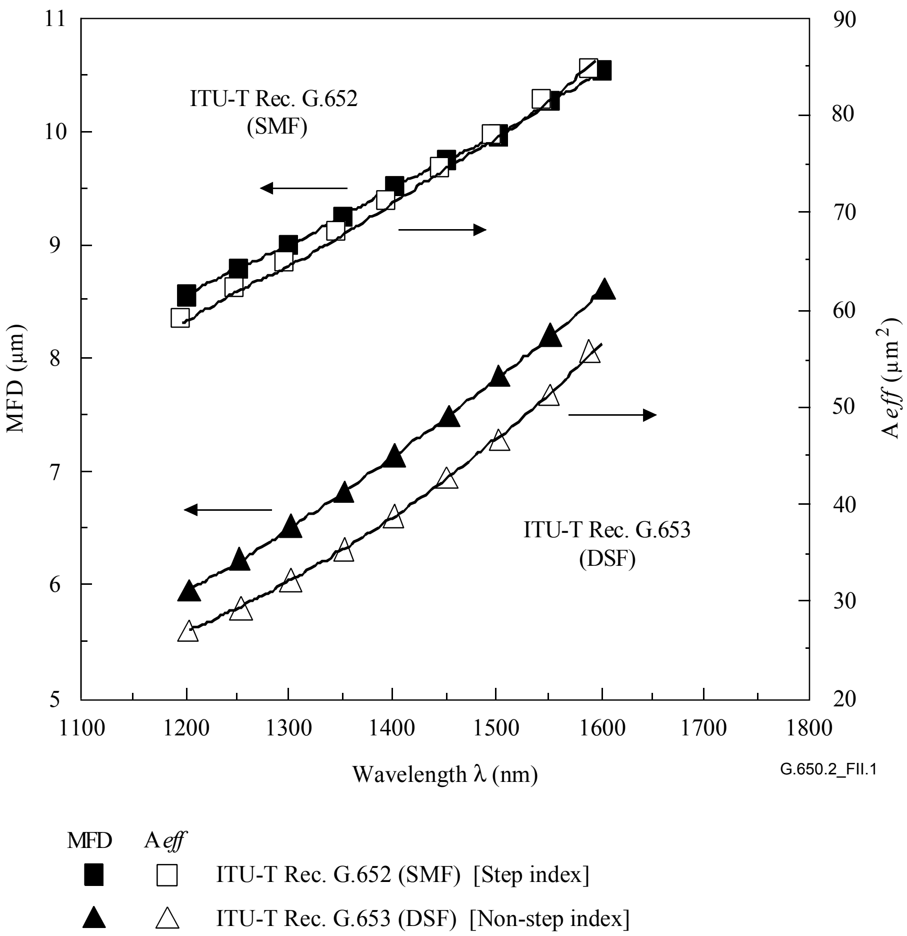
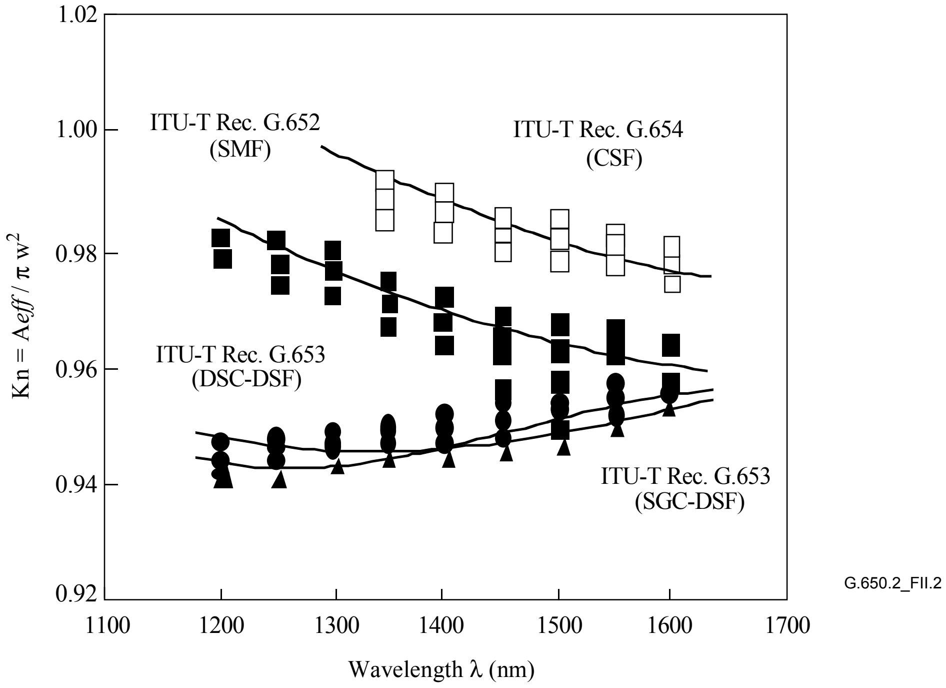


Figure II.1/G.650.2 – Example of measured wavelength dependence of A_{eff} and MFD (= 2W) of G.652 and G.653 fibres



[Step index] [Non-step index]

[Measured] ■ ITU-T Rec. G.652 (SMF) ● ITU-T Rec. G.653 (DSC-DSF)

□ ITU-T Rec. G.654 (CSF) ▲ ITU-T Rec. G.653 (SGC-DSF)

[Calcurated] [———]

DSC Dual Shape Core
SGC Segmented Core

Figure II.2/G.650.2 – Example of calculated and measured wavelength dependence of correction factor k for G.652, G.653 and G.654 fibres

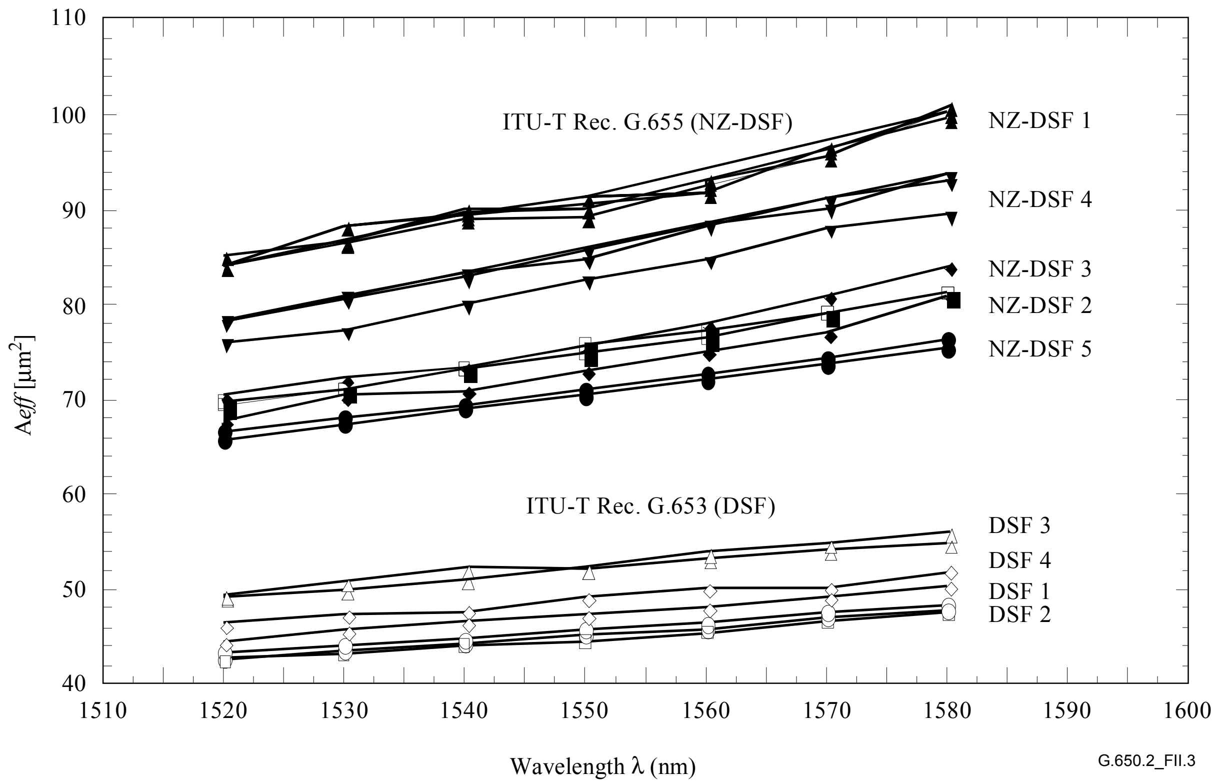


Figure II.3/G.650.2 – Example of measured λ dependence of A_{eff} for G.653 and G.655 fibres

II.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:

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

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.

II.5 Stimulated Brillouin scattering

II.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.

II.5.2 SBS threshold estimation for single-mode fibres

II.5.2.1 SBS threshold

In general, the SBS threshold is expressed as:

$$P_{th} = 21 \frac{KA_{eff}}{gL_{eff}} \frac{\Delta\nu_p + \Delta\nu_B}{\Delta\nu_B} \tag{II-6}$$

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 ($1 \le K \le 2$) 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:

$$L_{eff} = \frac{1 - \exp(-\alpha L)}{\alpha} \tag{II-7}$$

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 $\frac{\Delta\nu_p}{\Delta\nu_B} << 1$, 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:

$$P_m = 21 \frac{KA_{eff}}{gL_{eff}} \tag{II-8}$$

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, characterised as a function of mode field diameter for a given fibre design.

II.5.2.2 Experimental set-up for SBS threshold

Figure II.4 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 II.5 shows an example of the transmitted and backscattered power at 1.32 μm as a function of input power for a G.654 [3] 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 II.5). Table II.2 summarizes the fibre parameters and SBS thresholds for various fibre types.

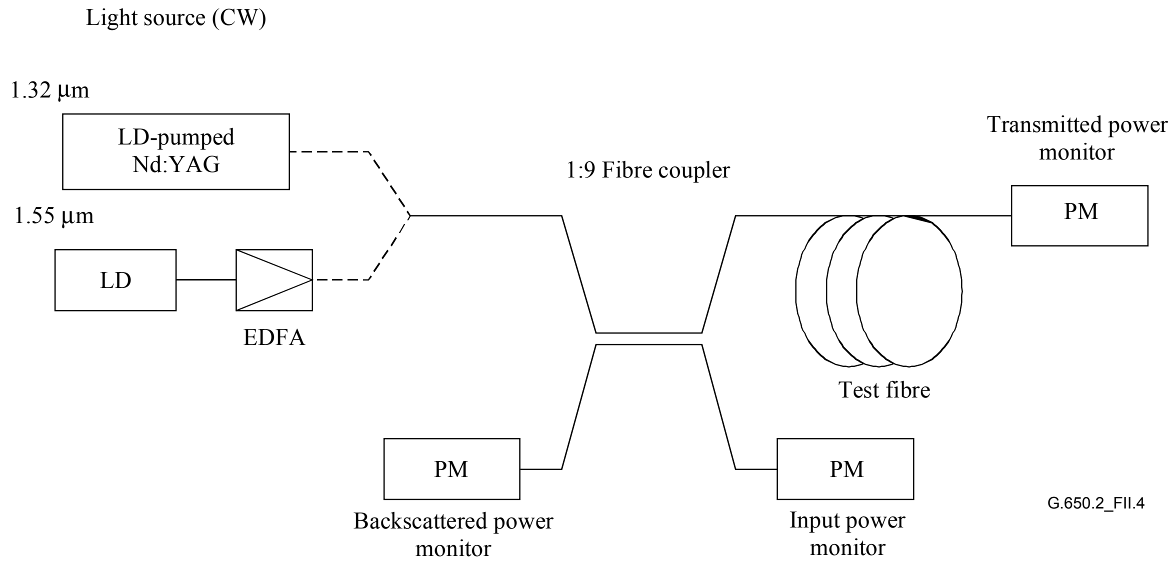


Figure II.4/G.650.2 – Experimental set-up

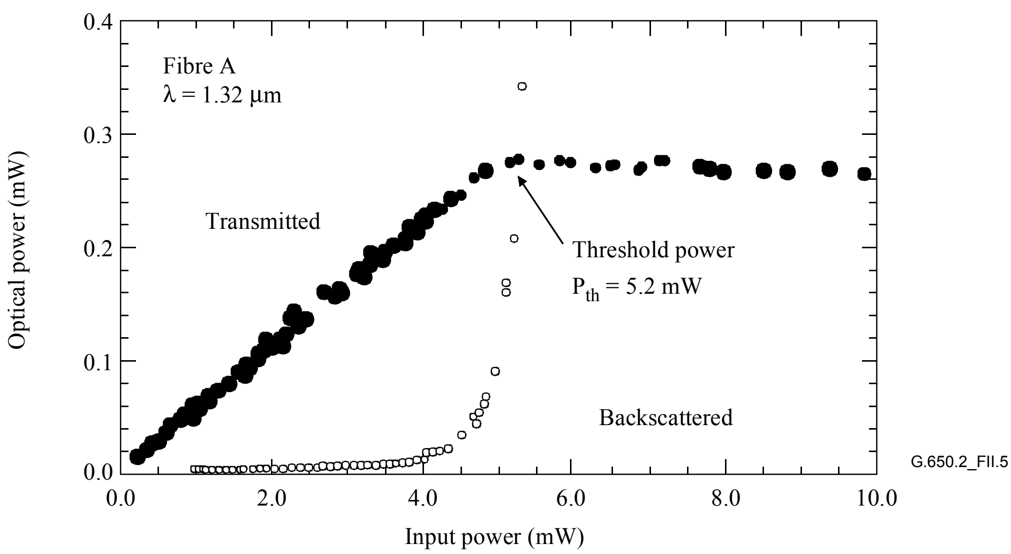


Figure II.5/G.650.2 – Transmitted and backscattered power as a function of input power

Threshold powers in Table II.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 II.2/G.650.2 – Test fibre parameters

Fibre		A	B	C	D	E	F	G
Fibre type		**ITU-T Rec. G.654**	**ITU-T Rec. G.652**	**ITU-T Rec. G.653**	**ITU-T Rec. G.653**	**ITU-T Rec. G.653**	**ITU-T Rec. G.653**	**ITU-T 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

II.5.2.3 SBS threshold estimation

Figure II.6 shows the relationship between SBS threshold and A_{eff}/L_{eff} for the test fibres. It shows that the SBS threshold is linearly dependent on A_{eff}/L_{eff}. The SBS threshold can be estimated as the following equation:

$$P_{th} = 0.11\left[\frac{A_{eff}}{L_{eff}}\right] \tag{II-9}$$

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

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

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

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 (II-9).

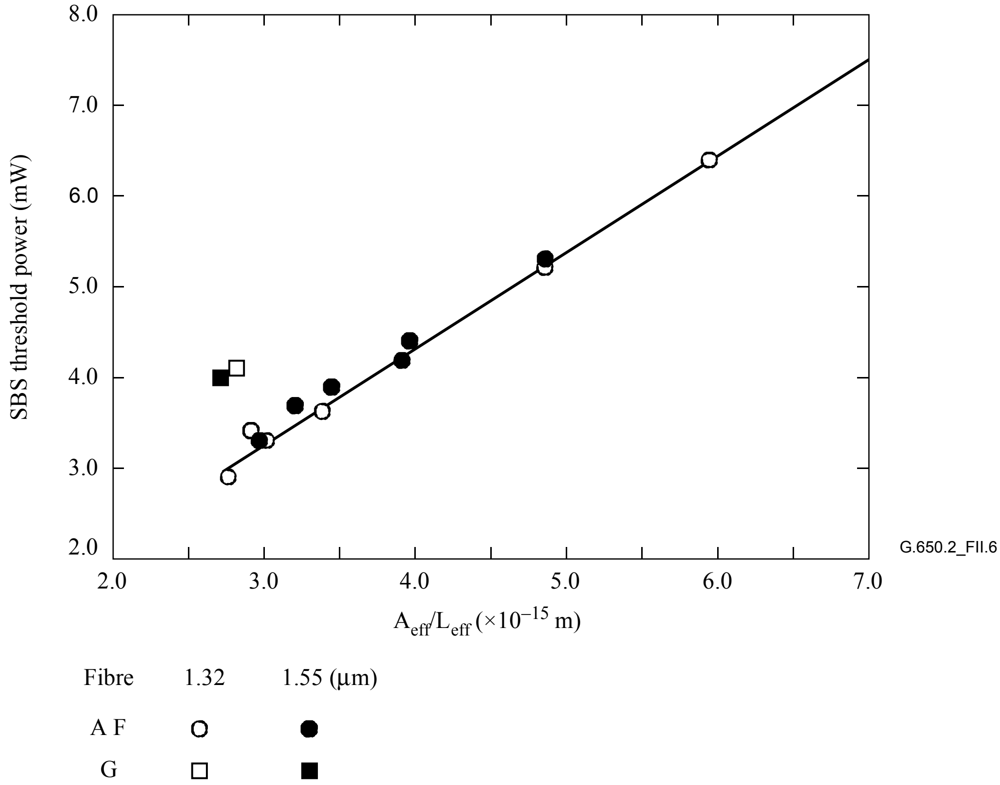


Figure II.6/G.650.2 – Relationship between SBS threshold and A_{eff}/L_{eff}

II.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.

Appendix III

Test methods for effective area (A_{eff})

III.1 The far-field scan (FFS) technique

III.1.1 General

The effective area (A_{eff}) of single mode optical fibres is determined by the far-field scan (FFS) technique.

III.1.2 Test apparatus

A schematic diagram of the test set-up for far-field scan (FFS) is shown in Figure III.1.

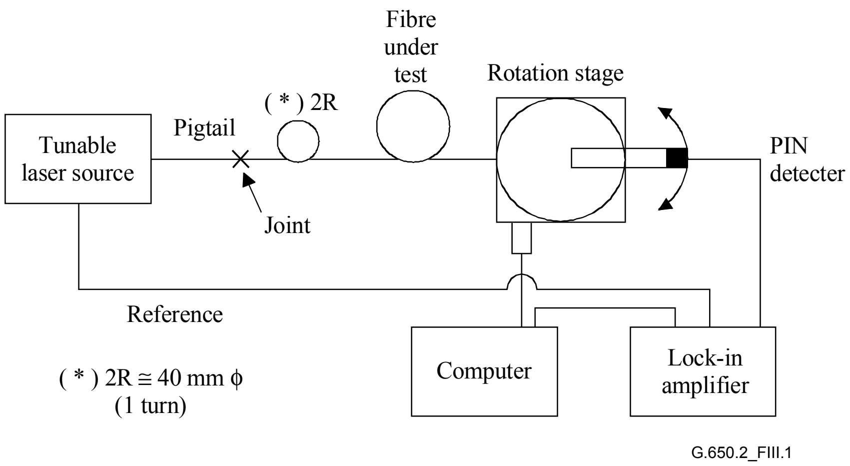


Figure III.1/G.650.2 – Typical arrangement of far-field scan (FFS) set-up

III.1.2.1 Light source (as in 5.1.1.2.1/G.650.1)

III.1.2.2 Modulation (as in 5.1.1.2.2/G.650.1)

III.1.2.3 Launching conditions (as in 5.1.1.2.3/G.650.1)

III.1.2.4 Cladding mode stripper (as in 5.1.1.2.4/G.650.1)

III.1.3.5 Specimen (as in 5.1.1.2.5/G.650.1)

III.1.2.6 Scan apparatus (as in 5.1.1.2.6/G.650.1)

III.1.2.7 Detector (as in 5.1.1.2.7/G.650.1)

III.1.2.8 Amplifier (as in 5.1.1.2.8/G.650.1)

III.1.2.9 Data acquisition (as in 5.1.1.2.9/G.650.1)

III.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 effective area (A_{eff}) is computed from Equation (III-1).

III.1.3.1 Equipment calibration

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

III.1.3.2 Calculations

III.1.3.2.1 Equations and figures for effective area (A_{eff}) calculation

1) Fold the far-field radiation power data:

Let P (θ_i) be the measured power as a function of angular position, θ_i (radians) indexed by i. The folded power curve, P_f (θ_i), for $0 \le \theta i \le \theta max$ is:

$$P_f(\theta i) = \frac{P(\theta_i) + P(-\theta_{-i})}{2} \qquad \text{(III-1)}$$

2) Compute the near-field intensity pattern:

Use an appropriate numerical integration method to compute the integrals of Equation (III-1). Equation (III-2) is an example. Any other integration method shall be at least as accurate.

Calculate the near-field values for a range of radii, r_j, values ranging from zero to a value large enough that the computed intensity at the maximum radius is less than 0.01% of the maximum intensity.

$$I(r_j) = \left[\sum_0^n P_f^{1/2}(\theta_1) J_0\left(\frac{2\pi r\, j \sin(\theta_i)}{\lambda}\right) \sin(2\theta_i)\Delta\theta \right]^2 \qquad \text{(III-2)}$$

where $\Delta\theta = \theta_1 - \theta_0$

3) Compute the integrals of Equation (III-2):

Use an appropriate numerical integration method to compute the integrals of Equation (III-2). Equation (III-3). is an example. Any other integration method shall be at least as accurate.

$$T = \left[\sum_0^m I(r_j) r_j \Delta r \right]^2 \qquad \text{(III-3)}$$

$$B = \sum_0^m I^2(r_j) r_j \Delta r \qquad \text{(III-4)}$$

where $\Delta r = r_1 - r_0$, and m is the number of positions measured.

4) Complete the calculation:

$$A_{eff} = \frac{2\pi T}{B} \qquad \text{(III-5)}$$

An example measured far-field power data is shown in Figure III.2.

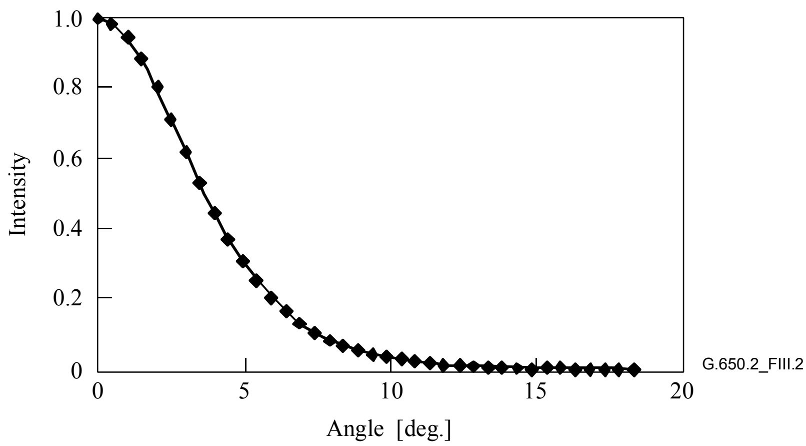


Figure III.2/G.650.2– Example of measured FFP data

III.1.4 Presentation of the results

The following details shall be presented:

a) Test set-up arrangement, dynamic range of the measurement system, processing algorithms, and a description of the 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) Effective area (A_{eff}).

j) Plot of A_{eff} (λ) (if required).

III.2 The variable aperture (VA) technique

III.2.1 General

The effective area (A_{eff}) of single-mode fibres is determined by the variable aperture in the far-field (VA) measurement technique.

III.2.2 Test apparatus

A schematic diagram of the test set-up for VA technique is shown in Figure III.3.

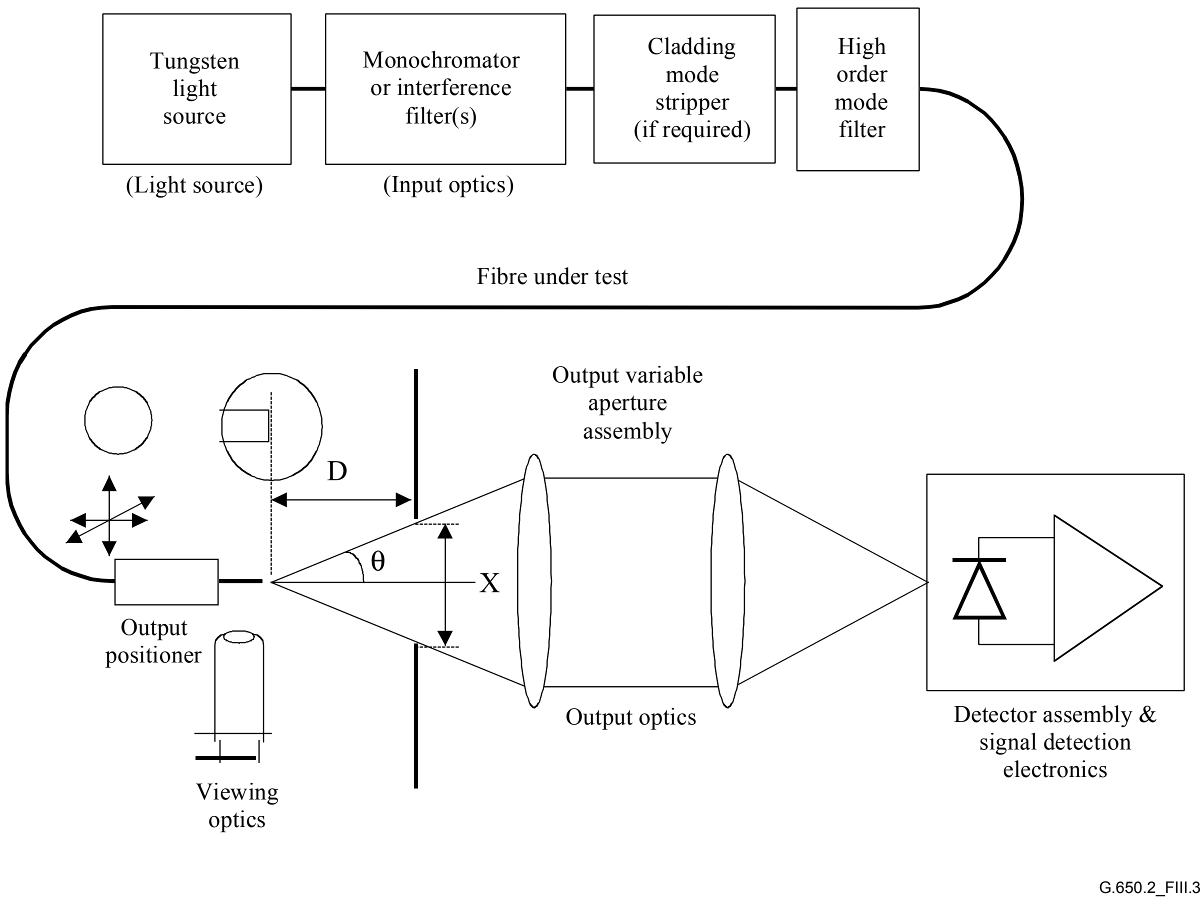


Figure III.3/G.650.2 – Typical arrangement of the variable aperture (VA) technique set-up

III.2.2.1 Light source (as in 5.1.1.2.1/G.650.1)

III.2.2.2 Modulation (as in 5.1.1.2.2/G.650.1)

III.2.2.3 Launching conditions (as in 5.1.1.2.3/G.650.1)

III.2.2.4 Cladding mode stripper (as in 5.1.1.2.4/G.650.1)

III.2.2.5 Specimen (as in 5.1.1.2.5/G.650.1)

III.2.2.6 Aperture apparatus

A mechanism containing at least twelve apparatus spanning the half-angle range of numerical apertures from 0.02 to 0.25 (0.4 for fibres covered by ITU-T Rec. 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.

III.2.2.7 Output variable aperture assembly

A device consisting of round transmitting apertures of various sizes (such as an aperture wheel), shall be placed a distance D of at least 100 w^2/λ from the fibre end, and is used to vary the power collected from the fibre output pattern. Typically 12 to 20 apertures are used and are located about 20-50 mm away from the fibre end. The maximum numerical aperture of the test set shall be = 0.40. Means of centering the apertures with respect to the pattern shall be employed to decrease sensitivity to fibre end-angle.

As part of equipment set-up (as shown in Figure III.4), carefully measure and record the longitudinal distance D between the fibre output end position and the aperture plane and the diameters X_i of each aperture. Determine the half-angle subtended by each aperture in the wheel and record these θ_i, (i = 1 to n in order of increasing aperture size) values for future calculation. These values are independent of test wavelength.

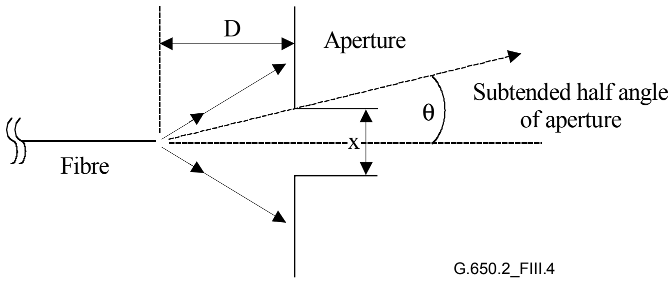


Figure III.4/G.650.2 – Aperture apparatus set-up

III.2.2.8 Detector (as in 5.1.1.2.7/G.650.1)

III.2.2.9 Amplifier (as in 5.1.1.2.8/G.650.1)

III.2.2.10 Data acquisition (as in 5.1.1.2.9/G.650.1)

III.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 effective area (A_{eff}) is computed from Equations (III-6) to (III-10).

III.2.3.1 Equipment calibration

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

III.2.3.2 Calculations

III.2.3.2.1 Equations and figures for effective area (A_{eff}) calculation

The variable aperture (VA) technique measures the total normalized power f (θ) passing through a given aperture as shown in Figure III.3 subtending a far-field angle θ at the fibre. These power values are equivalent to an integration of the normalized far-field power distribution $F^2(\theta)$. This is represented by Equation (III-6).

$$f(\theta) = \int_0^\theta F^2(\theta)\sin(\theta)d\theta \qquad \text{(III-6)}$$

A plot of normalized power transmitted through the apertures as a function of angle θ is shown in Figure III.5.

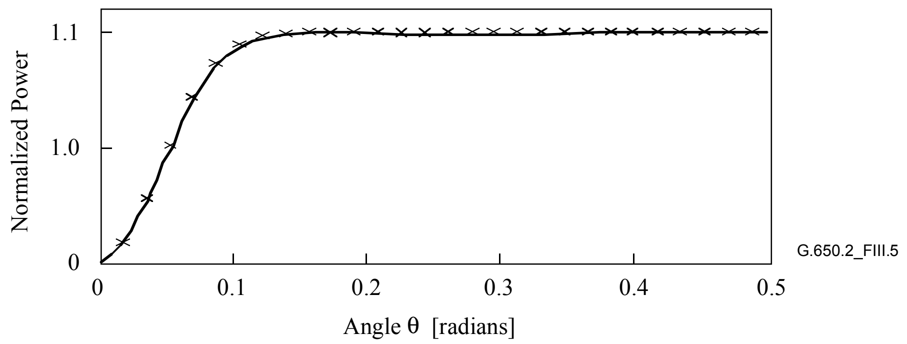


Figure III.5/G.650.2 – Plot of measured VA data

A quartic function is fitted to far-field aperture data, given by Equation (III-7):

$$f(\theta) = A\theta^4 + B\theta^3 + C\theta^2 + D\theta^1 + E \qquad \text{(III-7)}$$

Effective area, A_{eff}, is calculated from the near-field power distribution I (r) given as a function of radius r. To calculate this, one must first differentiate the integrated power data, $f(\theta)$, to give the far-field power distribution $F^2(\theta)$,

$$F^2(\theta) = \frac{df(\theta)}{d(\theta)} \cdot \frac{1}{\sin\theta} \qquad \text{(III-8)}$$

A plot of this calculated FFP distribution is shown in Figure III.6.

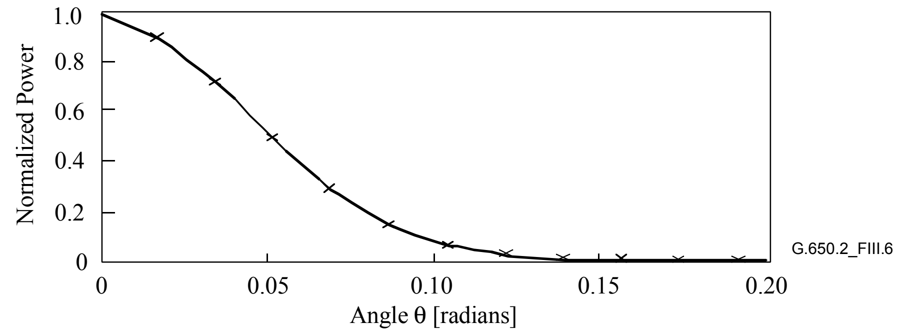


Figure III.6/G.650.2 – Plot of FFP distribution

From the far-field power distribution F^2 (θ) it is then possible to calculate the near-field power distribution I (r) as a function of radius r, using the inverse Hankel transform as follows:

$$I(r) = \left[\int_0^{\infty} \sqrt{F^2(\theta)} \cdot J_0\left(\frac{2\pi r}{\lambda}\right) \sin 2\theta d\theta \right]^2 \qquad \text{(III-9)}$$

A plot of this calculated near-field distribution I (r) as a function of radius r is shown in Figure III.7.

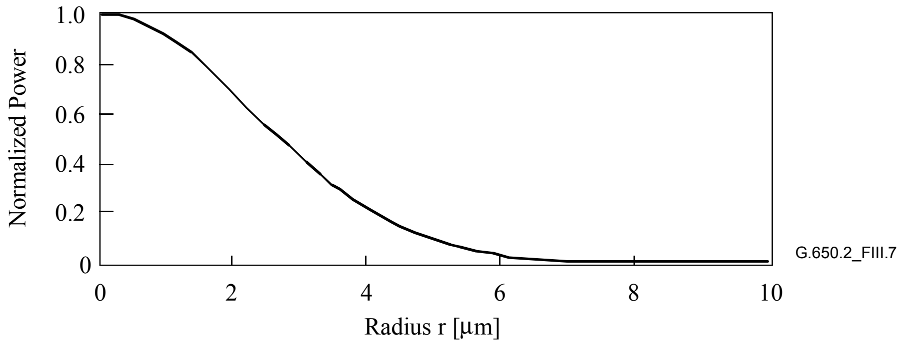


Figure III.7/G.650.2 – Plot of NFP distribution

Effective area, A_{eff} is then calculated from the near-field distribution I (r) using Equation (III-10).

$$A_{eff} = 2\pi \cdot \frac{\left[\int_0^{\infty} I(r) \cdot r dr \right]^2}{\int_0^{\infty} I(r)^2 \cdot r dr} \qquad \text{(III-10)}$$

III.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) Effective area (A_{eff}).

j) Plot of A_{eff} (λ) (if required).

III.3 The near-field scan (NFS) technique

III.3.1 General

The effective area (A_{eff}) of single mode fibres is determined by the near-field scan (NFS) measurement technique.

III.3.2 Test apparatus

III.3.2.1 Light source (as in 5.1.1.2.1/G.650.1)

III.3.2.2 Modulation (as in 5.1.1.2.2/G.650.1)

III.3.2.3 Launching conditions (as in 5.1.1.2.3/G.650.1)

III.3.2.4 Cladding mode stripper (as in 5.1.1.2.4/G.650.1)

III.3.2.5 Specimen (as in 5.1.1.2.5/G.650.1)

III.3.2.6 Scan apparatus (as in 5.1.1.2.6/G.650.1)

III.3.2.7 Detector (as in 5.1.1.2.7/G.650.1)

III.3.2.8 Amplifier (as in 5.1.1.2.8/G.650.1)

III.3.2.9 Data acquisition (as in 5.1.1.2.9/G.650.1)

III.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 effective area (A_{eff}) is computed from Equations (III-11) to (III-15).

III.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 dimension are already known with suitable accuracy. This magnification shall be recorded.

III.3.3.2 Calculations

III.3.3.2.1 Equations and figures for effective area (A_{eff}) calculation

1) Calculate the centroid:

   For a given cross-section of the near-field pattern (NFP) that is of maximum extent, with position values given by r and intensity values as I (r_i), the centroid position, r_c, is given as:

$$r_c = \frac{\sum r_i I(r_j)}{\sum I(r_i)} \qquad \text{(III-11)}$$

2) Fold the intensity profile:

   Re-index the position and intensity data around the position r_c so that positions above have index values greater than zero and positions below have index values less than zero. The maximum index is given as n. The folded intensity profile is:

$$I_f\ (r_i) = \{I\ (r_i) + I\ (r_{-i})\}/2 \qquad \text{(III-12)}$$

3) Compute the integrals from Equation (III-12):

   Use an appropriate numerical integration method to compute the integrals of Equation (III-12). The following is an example. Any other integration method shall be at least as accurate.

$$T = \left[\sum_0^m I(r_j) r_j \Delta r\right]^2 \qquad \text{(III-13)}$$

$$B = \sum_{0}^{m} I^2(r_j) r_j \Delta r \qquad \text{(III-14)}$$

where $\Delta r = r_1 - r_0$

4) Complete the calculation:

$$Aeff = \frac{2\pi T}{B} \qquad \text{(III-15)}$$

An example of calculated near-field pattern (NFP) is shown in Figure III.7.

III.3.4 Presentation of the results

The following details shall be presented:

a) Test set-up arrangement, dynamic range of the measurement system, processing algorithms, and a description of the 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) Effective area (A_{eff}).

j) Plot of $A_{eff}(\lambda)$ (if required).

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