CHAPTER 1

OPTICAL FIBRES CHARACTERISTICS

Introduction

This Chapter is devoted to the description of the main characteristics of the optical fibres. In clause 1 the difference between multimode and single-mode is outlined. Fibre design issues and fibre manufacturing methods are shortly dealt with in clauses 2 and 3. Clauses 4, 5, 6 and 7 are dedicated to the criteria adopted for the specification of the optical fibres in ITU-T (fibre attributes, cable attributes, link attributes). Clause 8 gives a glance to the test methods. Clause 9 describes the characteristics of the optical fibres specified in ITU-T and their possible applications. For a more detailed description of these applications see Chapter 8.

For further information on the content of this Chapter see Recommendations ITU-T G.650.1, ITU-T G.650.2, ITU-T G.650.3, ITU-T G.652, ITU-T G.653, ITU-T G.654, ITU-T G.655, ITU-T G.656, ITU-T G.657 and ITU-T G.651.1.

1　　Single-mode and multimode optical fibres

Multimode optical fibres are dielectric waveguides which can have many propagation modes. Light in these modes follows paths that can be represented by rays as shown in Figure 1-1a and 1-1b, where regions 1, 2 and 3 are the core, cladding and coating, respectively. The cladding glass has a refractive index, a parameter related to the dielectric constant, which is slightly lower than the refractive index of the core glass.
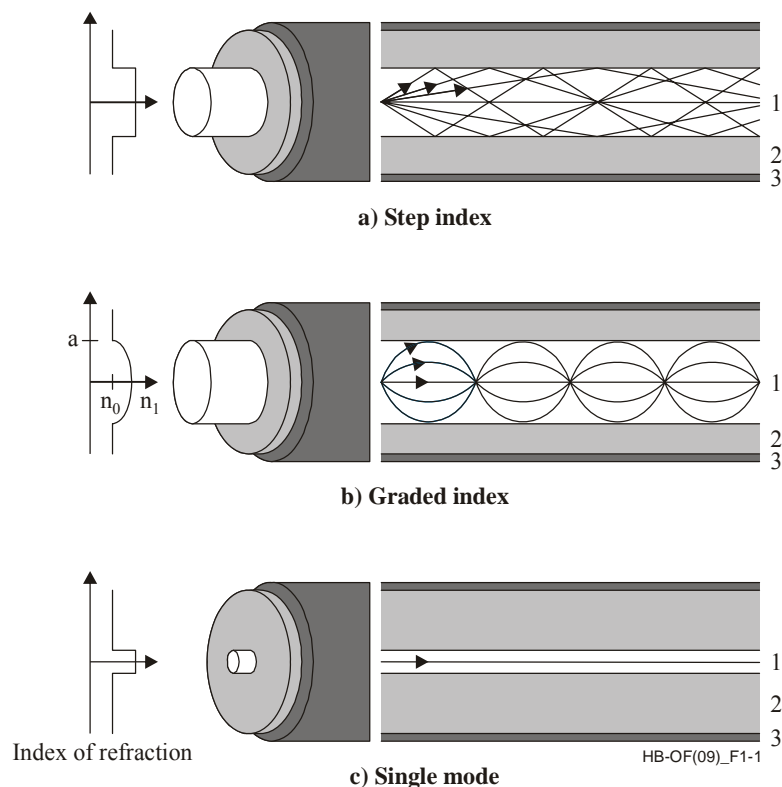

Figure 1-1 – The three principal types of fibres

The fibre in Figure 1-1a is called "step index" because the refractive index changes abruptly from cladding to core. As a result, all rays within a certain angle will be totally reflected at the core-cladding boundary. Rays striking the boundary at angles greater than this critical angle will be partially reflected and partially transmitted out through the boundary towards the cladding and coating. After many such reflections, the energy in these rays will eventually be lost from the fibre. Region 3, the coating, is a plastic which protects the glass from abrasion.

The paths along which the rays (modes) of this step-index fibre travel differ depending on their angle relative to the axis. As a result, the different modes in a pulse arrive at the far end of the fibre at different times, resulting in pulse spreading, which limits the bit rate of a digital signal that can be transmitted.

The different mode velocities can be nearly equalized by using a "graded-index" fibre as shown in Figure 1-1b. Here the refractive index changes smoothly from the centre out in a way that causes the end-to-end travel time of the different rays to be nearly equal, even though they traverse different paths. This velocity equalization can reduce pulse spreading by a factor of 100 or more. By reducing the core diameter and the refractive index difference between the core and the cladding only one mode (the fundamental one) will propagate and the fibre is then "single-mode" (Figure 1-1c). In this case there is no pulse spreading at all due to the different propagation time of the various modes.

The cladding diameter is 125 μm for all the telecommunication types of fibres. The core diameter of the multimode fibres is 50 μm, whereas that of the single-mode fibres is 8 to 10 μm.

2   Fibre design issues

As said above, in its simplest form a step-index fibre consists of a cylindrical core surrounded by a cladding layer whose index is slightly lower than that of the core. Both core and cladding use silica as the basic material, the difference in the refractive indexes is realized by doping the core or the cladding or both. Dopants such as GeO_2 and P_2O_5 increase the refractive index of silica and are suitable for the core. On the other hand, dopants such as B_2O_3 and fluorine decrease the refractive index of silica and are suitable for the cladding. The major design issues for the optical fibres are related to the refractive-index profile, to the amount of dopants, and the core and cladding dimensions.

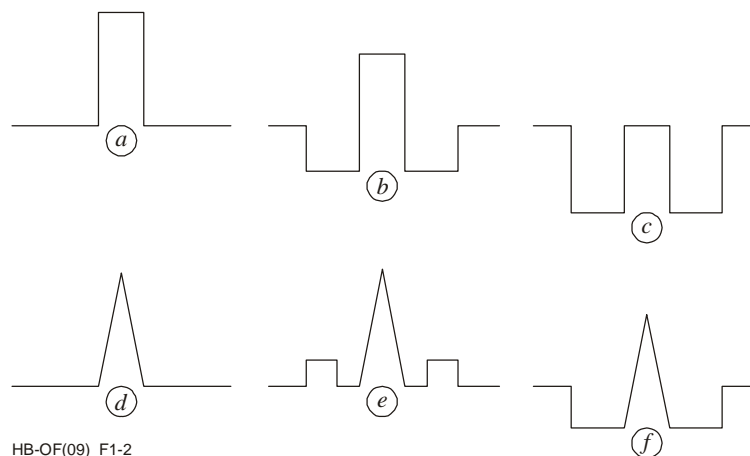Figure 1-2 shows typical index profiles that have been used for different types of fibres.

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Figure 1-2 – Examples of index profiles of single-mode fibres

The top row corresponds to standard fibres which are designed for having minimum dispersion near 1 300 nm with a cut-off wavelength in the range 1 100-1 200 nm. The simplest design (Figure 1-2a) consists of a pure silica cladding and a core doped with GeO_2. A commonly used variation (Figure 1-2b) has a reduced cladding index over a region adjacent to the core by fluorine doping. It is also possible to have an

undoped core using a design shown in Figure 1-2c. The fibres of these last two types are referred to as depressed cladding fibres. They are also called W fibres reflecting the shape of the index profile. The bottom row of Figure 1-2 shows three index profiles used for the dispersion-shifted fibres which have the zero-dispersion wavelength in the range 1 450-1 600 μm. A step or triangular index profile with a depressed or raised cladding is often used for this purpose. The refractive indexes and the thicknesses of the different layers are optimized to design a fibre with the desirable dispersion characteristics.

3   Fibre manufacturing methods

Preparation of silica fibres consists of two major processes: preform making and drawing. The attenuation and the dispersion characteristics of optical fibres largely depend on the preform making process, while glass geometry characteristics and strength depend on the drawing process. These two processes are shortly described in the following.

Several methods can be used to make the preforms. The four commonly used methods are modified chemical-vapour deposition (MCVD), plasma-activated chemical-vapour deposition (PCVD), outside-vapour deposition (OVD) and vapour-axial deposition (VAD).

The second process (drawing) of the preparation of a fibre is essentially the same, irrespective of the process used to make the preform.

Figure 1-3 shows the drawing apparatus schematically.
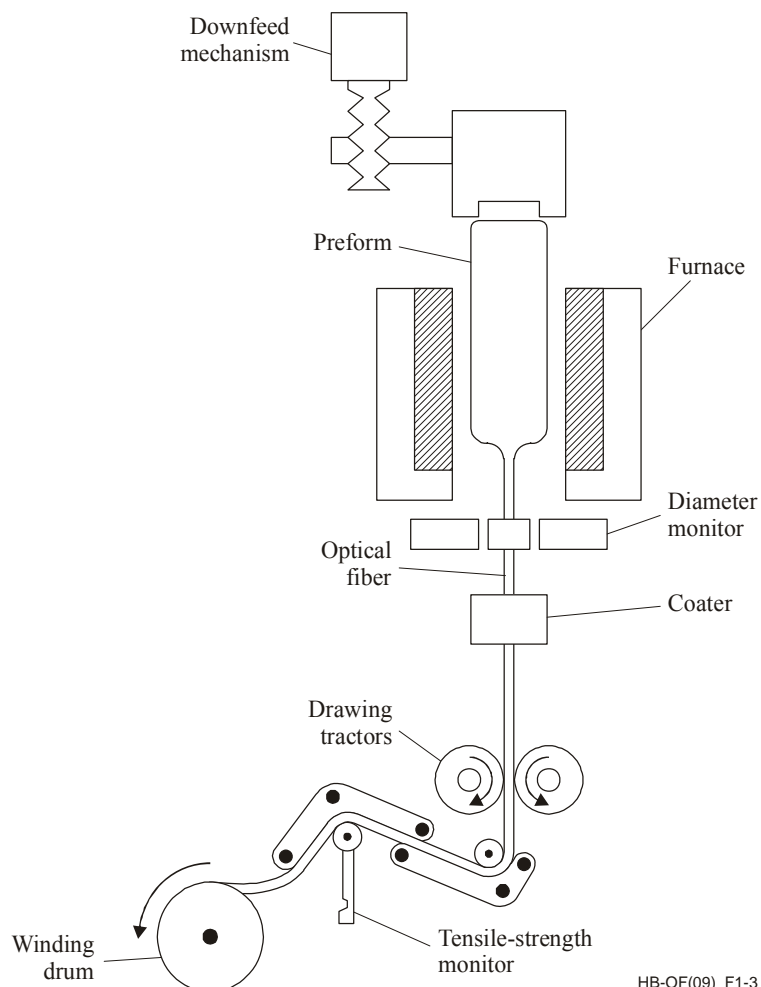
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Figure 1-3 – Apparatus for fibre drawing

The preform is fed into a furnace in a controlled manner where it is heated to a temperature of about 2 000° C. The melted preform is drawn into a fibre by using a precision-feed mechanism. The fibre diameter is monitored optically by dedicated measurement equipment. The fibre diameter can be kept constant to within 0.1%. A polymer coating is applied to the fibre during the drawing step. It serves a dual purpose, as it provides mechanical protection and preserves the transmission properties of the fibre. The diameter of the coated fibre is typically 245 μm, although it can be as large as 900 μm when multiple coatings are applied.

A proof-stress which breaks weak spots is applied while the fibre is winding on the drum. This proof-stress can be applied either on-line during the drawing process, or off-line as a separate process step. The proof-test is a main reliability tool.

4   Specification of the optical fibres characteristics

The optical fibres are specified in ITU-T with reference to the geometrical, optical, transmission and mechanical attributes listed in Table 1-1. However, as shown in the same table, for some attributes there is not the specification of a value or limit.

Fibre attributes are those that are retained throughout cabling and installation. Among the fibre attributes only those providing a minimum essential design framework for fibre manufacture are recommended (e.g. mode field diameter, cladding diameter, cut-off wavelength, macrobending loss). Chromatic dispersion coefficient is also included in these attributes.

Cable attributes are recommended for cables in factory lengths as they are delivered. The attenuation coefficient and the polarization mode dispersion (PMD) coefficient are included among the cable attributes since they can be affected by the cabling process.

Link attributes are characteristic of concatenated cables. A concatenated link usually includes a number of spliced factory lengths of optical fibre cable. The transmission parameters for concatenated links must take into account not only the performance of the individual cable factory lengths, but also the statistics of concatenation. The transmission characteristics of the factory length optical fibre cables will have a certain probability distribution which often needs to be taken into account if the most economic designs are to be obtained. Link attributes are affected by factors other than optical fibre cables by such things as splices, connectors and installation.

The definitions and the characteristics of all these attributes are given in the following clauses.

5   Fibre attributes

Fibre attributes are those characteristics that are retained throughout cabling and installation processes. The values specified for each type of fibre can be found in the appropriate ITU-T Recommendation for multimode fibre (Recommendation ITU-T G.651.1) or single-mode fibre Recommendations ITU-T G.652, …, G.657.

5.1   Core characteristics

A value for the *core diameter* and for *core non-circularity* is specified for multimode fibres.

The *core centre* is the centre of a circle which best fits the points at a constant level in the near-field intensity pattern emitted from the central region of the fibre, using wavelengths above and/or below the fibre's cut-off wavelength. Usually the core centre represents a good approximation of the mode field centre (see § 5.2). The *cladding centre* is the centre of a circle which best fits the cladding boundary. The *core concentricity error* is the distance between the core centre and the cladding centre.

Table 1-1 – Fibre, cable and link attributes

	Unit	Relevant for single-mode fibres	Value specified by ITU-T	Relevant for multimode fibre	Value specified by ITU-T
Fibre attributes					
Core diameter	μm	–	–	Yes	Yes
Core non-circularity	%	–	–	Yes	Yes
Mode field diameter	μm	Yes	Yes	–	–
Effective area	μm²	Yes	No	–	–
Core concentricity error	μm	Yes	Yes	Yes	Yes
Cladding diameter	μm	Yes	Yes	Yes	Yes
Cladding non-circularity	%	Yes	Yes	Yes	Yes
Cut-off wavelength	nm	Yes	Yes	–	–
Numerical aperture		–	–	Yes	Yes
Macrobending loss	dB/turn or dB	Yes	Yes	Yes	Yes
Microbending loss	dB/km	Yes	No	Yes	No
Fibre and protective materials		Yes	No	Yes	No
Protective materials		Yes	No	Yes	No
Proof-stress level	GPa	Yes	Yes	Yes	Yes
Refractive index profile		Yes	No	Yes	No
Modal bandwidth	MHz • km	–	–	Yes	Yes
Longitudinal uniformity of chromatic dispersion		Yes	No	–	–
Chromatic dispersion coefficient	ps/(nm • km)	Yes	Yes	Yes	Yes
Cable attributes					
Attenuation coefficient	dB/km	Yes	Yes	Yes	Yes
Polarization mode dispersion coefficient	ps/√km	Yes	Yes	–	–
Modal bandwidth	MHz • km	–	–	Yes	No
Link attributes					
Attenuation	dB	Yes	Yes	–	–
Chromatic dispersion	ps/nm	Yes	Yes	–	–
Differential group delay	Ps	Yes	Yes	–	–
Non-linear coefficient	W^{-1}	Yes	No	–	–

The tolerances on the physical dimensions of an optical fibre (core, mode field, cladding) are the primary contributors to splice loss and splice yield in the field. The maximum value for these tolerances (concentricity errors, non-circularities, etc.) specified in ITU-T Recommendations help to reduce systems costs and support a low maximum splice-loss requirement typically around 0.1 dB. Fibres with tightly controlled geometry tolerances will not only be easier and faster to splice, but will also reduce the need for testing in order to ensure high-quality splice performance. This is particularly true when fibres are spliced by passive, mechanical or fusion techniques for both single fibres and fibre ribbons (see Chapter 2).

5.2   Mode field characteristics

The *mode field* is the single-mode field distribution of the fundamental mode (LP_{01}) giving rise to a spatial intensity distribution in the fibre. For step-index fibres, the mode field can be well represented as a two-dimensional Gaussian form. The *mode field diameter* (MFD) represents a measure of the transverse extent of the electromagnetic field intensity of the mode in a single-mode fibre cross-section. Mode field diameter describes the size of the light carrying portion of the fibre. For single-mode fibre this portion includes the fibre core as well as a small portion of the surrounding cladding glass. MFD is an important parameter for determining the fibre resistance to bend induced loss and can affect splice loss as well. MFD, rather than the core diameter, is the functional parameter that determines optical performance when a fibre is coupled to a light source. It is a function of wavelength, core diameter and the refractive index difference between the core and the cladding.

5.3   Effective area (A_{eff})

Effective area (A_{eff}) 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. For Gaussian-shaped fields, A_{eff} is very close to $\pi MFD^2/4$.

5.4   Cladding characteristics

The *cladding* is the outermost region of glass in the fibre cross-section. The *cladding centre* is the centre of a circle which best fits the cladding boundary. The *cladding diameter* is the diameter of the circle defining the cladding centre. The *cladding non-circularity* is the difference between the maximum and minimum radii divided by the radius of the best fit circle, expressed as a percent.

As above said, the nominal value of the cladding diameter is 125 µm for all the types of optical fibres specified in ITU-T. A tolerance is also specified and the cladding deviation from nominal shall not exceed the specified tolerance.

5.5   Cut-off wavelength

Theoretical cut-off wavelength is the shortest wavelength at which only the fundamental (LP_{01}) mode can propagate in a single-mode fibre. At wavelengths below the theoretical cut-off wavelength, several modes propagate and the fibre is no longer single-mode, but multimode. This parameter can be computed from the refractive index profile of the fibre.

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

Cut-off wavelength is defined as the wavelength greater than which the ratio between the total power, including launched higher order modes and the fundamental mode power has decreased to less than 0.1 dB. According to this definition, the second order (LP_{11} or LP_{02} for some profiles) mode undergoes 19.3 dB more attenuation than the fundamental (LP_{01}) mode when the modes are equally excited.

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

Jumper cable cut-off wavelength λ_{cj} is measured on jumper cables in the following configuration: 2 metres, with one loop of $\times$ mm radius, often specified as 76 mm, with the rest of the jumper cable kept essentially straight.

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

Fibre cut-off wavelength and mode field diameter can be combined to estimate a fibre's bend sensitivity. High fibre cut-off and a small mode field diameter result in a more bend resistant fibre. However all practical installation techniques and cable designs should ensure a cable cut-off wavelength below the operating wavelength.

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

Alternative configurations may be used if the empirical results are demonstrated to be equivalent within 10 nm. For example, two 40 mm radius loops in a two-meter length of uncabled fibre meets this equivalent criterion for some fibre and cable designs.

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

$$\lambda_{cc} < \lambda_s$$

This ensures that each individual cable section is sufficiently single mode. Any joint that is not perfect will create some higher order (LP_{11}) mode power and single-mode fibres typically support this mode for a short distance (on the order of metres, depending on the deployment conditions). A minimum distance must be specified therefore between joints, in order to give the fibre sufficient distance to attenuate the LP_{11} mode before it reaches the next joint. If the above inequality is satisfied in the shortest cable section, it will be satisfied automatically in all longer cable sections, and single-mode system operation will occur regardless of the elementary section length.

Since specification of cable cut-off wavelength, λ_{cc}, is a more direct way of ensuring single-mode cable operation, specifying this is preferred to specifying fibre cut-off wavelength (λ_c) in Recommendations ITU-T G.652 through ITU-T G.657.

5.6   Numerical aperture

The numerical aperture (*NA*) is the sine of the vertex half-angle of the largest cone of rays that can enter or leave the core of an optical fibre, multiplied by the refractive index of the medium in which the vertex of the cone is located. All values are measured at 850 nm. The value of the numerical aperture is about 5% lower than the value of the maximum theoretical numerical aperture NA_{tmax} which is derived from a refractive index measurements trace of the core and cladding:

$$NA_{tmax} = \left(n_1^2 - n_2^2 \right)^{\frac{1}{2}}$$

in which n_1 is the maximum refractive index of the core and n_2 is the refractive index of the innermost homogeneous cladding.

5.7   Macrobending loss

For *single-mode fibres* macrobending loss varies with wavelength, bend radius and number of turns about a mandrel with a specified radius. Therefore, the limit for the macrobending loss is specified in ITU-T Recommendations for defined wavelength(s), bend radius, and number of turns.

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

For *multimode fibres* the launch condition is of paramount importance for macrobending loss, in particular the presence of higher order modes which are the most sensitive being stripped off due to bending. The mode distribution encountered at a specific macrobend may depend on how many macrobends precede it. For example, the first bend might influence the launch condition at the second bend, and the second bend might influence the launch condition at the third bend, etc. Consequently, the macrobending added loss at a given bend might be different than the macrobending added loss at another bend. In particular, the first bend may have the largest influence on following bends. Consequently, the macrobending added loss produced by multiple bends should not be expressed in the units of "dB/bend" by dividing the total added loss by the number of bends, but in dB for the specified number of bends.

5.8   Fibre and protective materials

The substances of which the fibres are made should be known because care may be needed in fusion splicing fibres of different substances. However adequate splice loss and strength can be achieved when splicing different high-silica fibres.

The physical and chemical properties of the material used for the fibre primary coating and the best way of removing it (if necessary for the splicing of the fibres) should be indicated.

The primary coating is made by the layer(s) of protective coating material applied to the fibre cladding during or after the drawing process to preserve the integrity of the cladding surface and to give a minimum amount of required protection (e.g. a 250 µm protective coating).

A secondary coating made by layer(s) of coating material can be applied over one or more primary coated fibres in order to give additional required protection or to arrange fibres together in a particular structure, e.g. a 900 µm "buffer" coating, "tight jacket", or a ribbon coating (see Chapter 2).

5.9 Proof-stress level

The fibre mechanical performance is largely dependent on the application of a proof-stress to the whole length of fibre. The optical fibre proof-test is characterized by the load applied to the fibre or the fibre elongation. The proof-stress level is the value of tensile stress or strain to which a full length of fibre is subjected for a specified short time period. This is usually done sequentially along the fibre length. The level of the proof-stress is determined as a function of the cable structure.

5.10 Refractive index profile

The refractive index profile is the refractive index across a diameter of the fibre. The refractive index profile of the fibre does not generally need to be known and therefore it is not specified in the ITU-T Recommendations.

5.11 Modal bandwidth

The different velocities of the various modes propagating in a graded-index multimode fibre can be nearly equalized by using a refractive index profile that changes smoothly from the centre to the cladding in a way that causes the end-to-end travel time of the different rays to be nearly equal, even though they travel different paths (see § 5.1.1). This is shown by the following approximated relation between the refractive index "*n*" and the radial co-ordinate "*r*":

$$n\,(r) \approx n_1 \left[\, 1 - \Delta\,(r/a)^g \,\right]$$

where:

a : core radius,

g : index profile shape parameter and

Δ : $(n_1 - n_0)/n_1$

where:

$n_1 = n_{(0)}$ and

$n_0 = n_{2(a)}$.

A more correct version is given as follows.

Following the notation of Snyder & Love, the quadratic index profile is given by:

$$n^2(r) = n_{co}^2 (1 - 2\Delta R^g)$$

where:

$$\Delta = \frac{n_{co}^2 - n_{cl}^2}{2n_{co}^2} \qquad R = \frac{r}{a}$$

n_{co} : refractive index at the core centre

n_{cl} : refractive index of the cladding

a : core edge (μm)

r : radius within the core.

The profile shape parameter "*g*" has an optimal value around 2 (parabolic profile) that most nearly equalizes the group velocities of the propagating modes.

However, in practice, small perturbations from the ideal profile are generally present and this leads to differences among the group velocities of the various modes higher values than the theoretical ones (Figure 1-4). The result of this modal dispersion is a limitation of the available bandwidth.
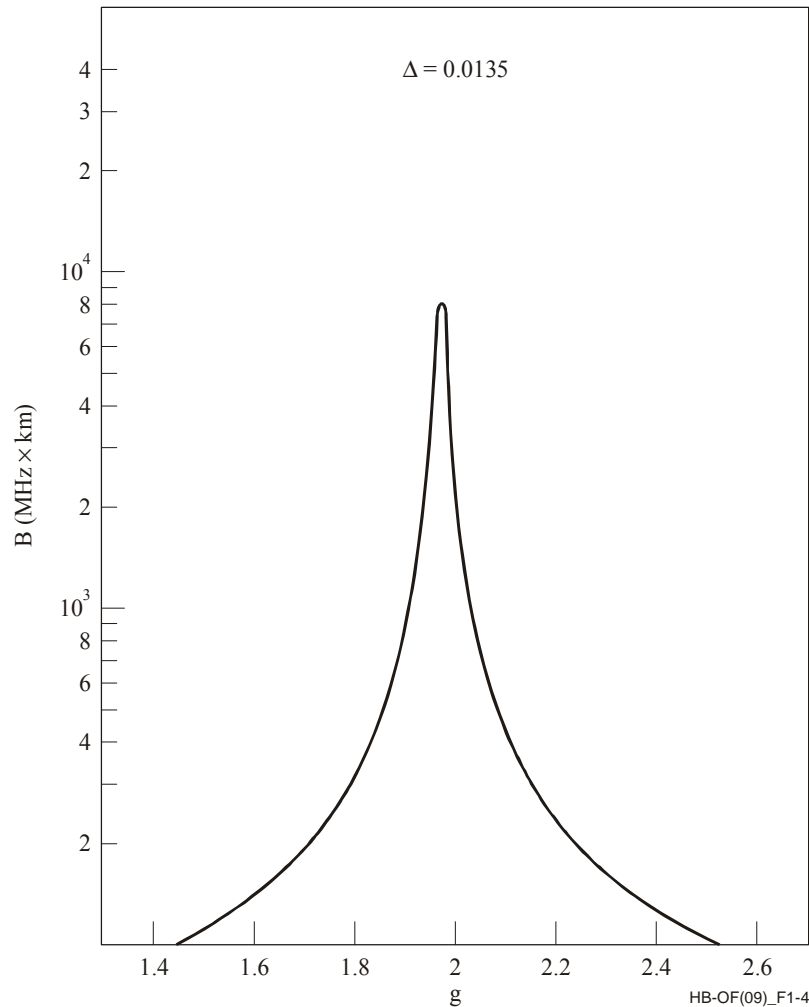

Figure 1-4 – Modal dispersion: Theoretical dependence of bandwidth on profile parameter "g"

The modal bandwidth is specified with a minimum value at one or more wavelengths in both the 850 nm and 1 300 nm regions. The optical fibre modal bandwidth shall not be lower than the recommended values. By convention, the modal bandwidth is linearly normalized to 1 km.

5.12   Chromatic dispersion

Chromatic dispersion is caused by delay differences among the group velocities of the different wavelengths composing the source spectrum. The consequence of the chromatic dispersion is a broadening of the transmitted impulses (Figure 1-5).
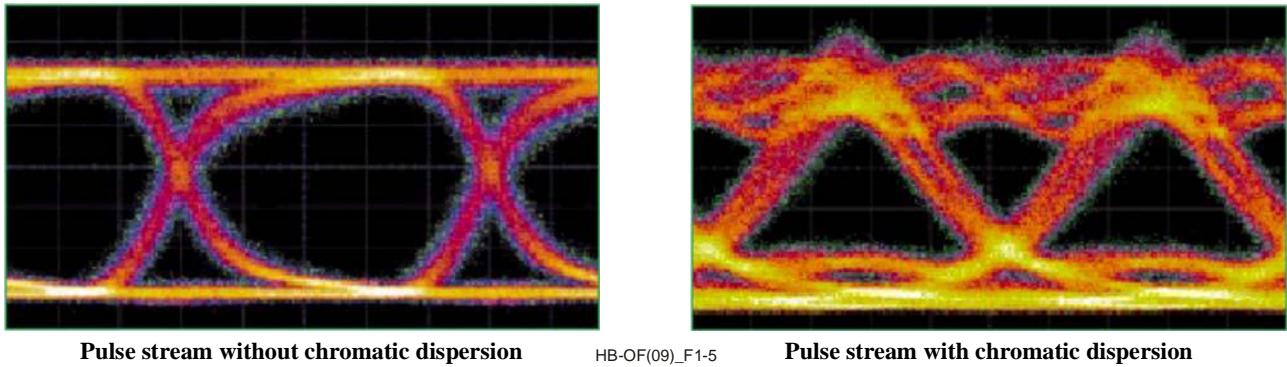
Pulse stream without chromatic dispersion   HB-OF(09)_F1-5   Pulse stream with chromatic dispersion

Figure 1-5 – The effect of the chromatic dispersion: pulse broadening and eye closing

The chromatic dispersion is essentially due to two contributions: material dispersion and waveguide dispersion. The *material dispersion* occurs because the refractive index of silica (and hence the group velocities) changes with the optical frequency (wavelength). It is generally the dominant contribution, except in the wavelength region in which it vanishes (for silica based material this happens around 1 300 nm).

The *waveguide dispersion* depends on the dispersive properties of the waveguide itself (e.g. the core radius and the index difference). An example of the interplay between these two contributions in the total dispersion is given in Figure 1-6. From a practical point of view, a significant property is that the waveguide dispersion has opposite signs with respect to the material dispersion in the wavelength range above 1 300 nm.
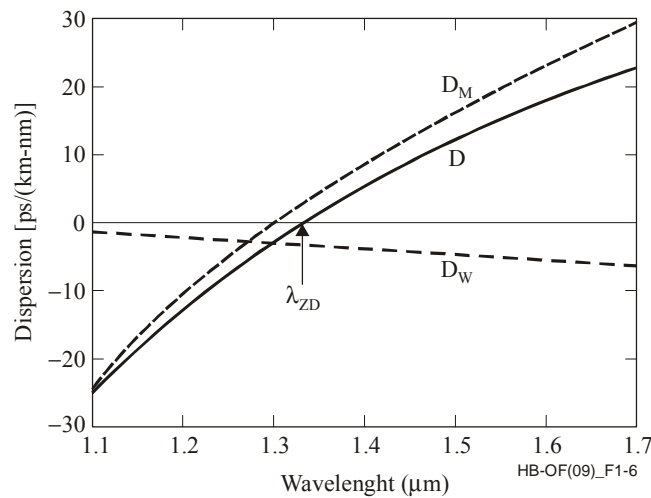

Figure 1-6 – Total dispersion D and relative contribution of material dispersion DM and waveguide dispersion DG for a conventional single-mode fibre

This property can be used to develop dispersion shifted fibres choosing suitable values for the core radius and for the index difference. The wavelength of the zero dispersion is moved from the region of 1 300 nm versus the region around 1 550 nm to coincide with the minimum loss region.

5.12.1 Chromatic dispersion definitions

Chromatic dispersion is the spreading of a light pulse in an optical fibre caused by the different group velocities of the different wavelengths composing the source spectrum. *Group delay* is the time required for a light pulse to travel a unit length of fibre. The group delay as a function of wavelength is denoted by $\tau(\lambda)$.

It is usually expressed in ps/km. *Chromatic dispersion coefficient* is the change of the group delay of a light pulse for a unit fibre length caused by a unit wavelength change. Thus, the chromatic dispersion coefficient is $D(\lambda) = d\tau/d\lambda$. It is usually expressed in ps/nm • km. *Chromatic dispersion slope* is the slope of the chromatic dispersion coefficient versus wavelength curve. The dispersion slope is defined as $S(\lambda) = dD/d\lambda$. *Zero-dispersion wavelength* is the wavelength at which the chromatic dispersion vanishes. *Zero-dispersion slope* is the chromatic dispersion slope at the zero-dispersion wavelength.

5.12.2   Chromatic dispersion coefficient

The chromatic dispersion coefficient, *D*, is specified within a wavelength range. There are two methods for specifying the limits, the original method, which is a box-like specification, and a newer method, in which the dispersion coefficient values are bound by a pair of curves.

In the *original specification form* the chromatic dispersion coefficient, *D*, is specified within a wavelength range, by stating a range of allowed absolute values of the chromatic dispersion coefficient. Particular types of fibre – the so-called non-zero dispersion-shifted single-mode fibres (e.g. those described in Recommendations ITU-T G.655 and ITU-T G.656) have an additional requirement that the chromatic dispersion coefficient shall not cross zero within the specified wavelength range. The sign of the chromatic dispersion is also specified. The form of such a specification is:

$$D_{min} \le |D(\lambda)| \le D_{max} \qquad \text{for} \quad \lambda_{min} \le \lambda \le \lambda_{max}$$

Values for D_{min}, D_{max}, λ_{min}, λ_{max} and sign are specified for each type of optical fibre.

In the *specification based on a pair of limiting curves* for each wavelength, λ, the chromatic dispersion coefficient, $D(\lambda)$, shall be restricted to a range of values associated with two limiting curves, $D_{min}(\lambda)$ and $D_{max}(\lambda)$, for one or more specified wavelength ranges defined in terms of λ_{min} and λ_{max}. The bounding curves may vary from one wavelength range to another; see for example the solid lines in Figure 1-7, representing the specification for ITU-T G.655.D fibres. The dotted lines show some individual distributions of commercial fibres.
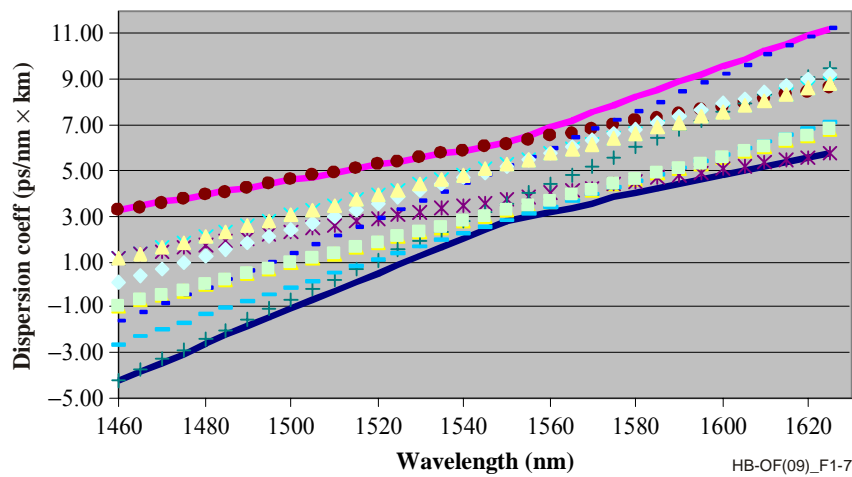

**Figure 1-7 – Specification of the chromatic dispersion coefficient
based on a pair of limiting curves**

The requirements on chromatic dispersion follow from wavelength-division-multiplexing (WDM) system design, which must balance first order chromatic dispersion with various non-linear effects, such as four-wave mixing, cross-phase modulation, modulation instability and stimulated Brillouin scattering (see Chapter 7).

5.12.3 Longitudinal uniformity of chromatic dispersion

At a particular wavelength, the local absolute value of chromatic dispersion coefficient can vary away from the value measured on a long length. If the value decreases to a small value at a wavelength that is close to an operating wavelength in a WDM system, four-wave mixing can induce the propagation of power at other wavelengths, including other operating wavelengths. The magnitude of the four-wave mixing power is a function of the absolute value of chromatic dispersion coefficient, the chromatic dispersion slope, the operating wavelengths, the optical power, and the distance over which four-wave mixing occurs (see Chapter 7).

6 Cables attributes

Cable attributes are those recommended for cables as they are delivered.

6.1 Attenuation

The *attenuation A(λ) at wavelength* λ of a fibre between two cross-sections, 1 and 2, separated by distance *L* is defined, as:

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

where:

$P_1(\lambda)$: optical power traversing the cross-section 1, and

$P_2(\lambda)$: optical power traversing the cross-section 2 at the wavelength λ.

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

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

The attenuation coefficient depends on the wavelength of transmitted light. Figure 1-8 shows the attenuation spectrum of a conventional and of a low water peak fibre.
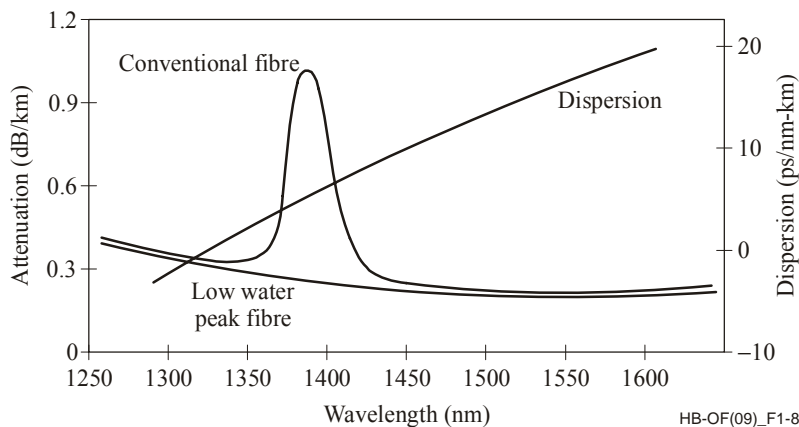

Figure 1-8 – Attenuation of an optical fibre

The conventional fibre exhibits a secondary minimum around 1 310 nm and an absolute minimum near 1 550 nm. In older fibre (e.g. ITU-T G.652.B) a strong peak of attenuation was present around 1 383 nm due to the presence of the residual water vapour in silica (OH ion). In modern low water peak fibre

(e.g. ITU-T G.652.D) the concentration of the OH ion is drastically reduced and the attenuation peak around 1 383 nm has practically disappeared. The low water peak fibre allow the possibility of using a larger wavelength range in respect of older fibres, in particular for WDM system applications.

The attenuation coefficient is specified with a maximum value at one or more wavelengths in both the 1 310 nm and 1 550 nm regions. The attenuation coefficient may be calculated across a spectrum of wavelengths, based on measurements at a few (3 to 4) predictor wavelengths. This procedure is described in Recommendation ITU-T G.650.1 and an example is given in Recommendation ITU-T G.650.1.

6.2 Polarization mode dispersion

Polarization mode dispersion (PMD) is related to the differential group delay (DGD), the time difference in the group delays between two orthogonal polarized modes, which causes pulse spreading in digital systems and distortions in analogue systems.

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 polarization modes (Figure 1-9).
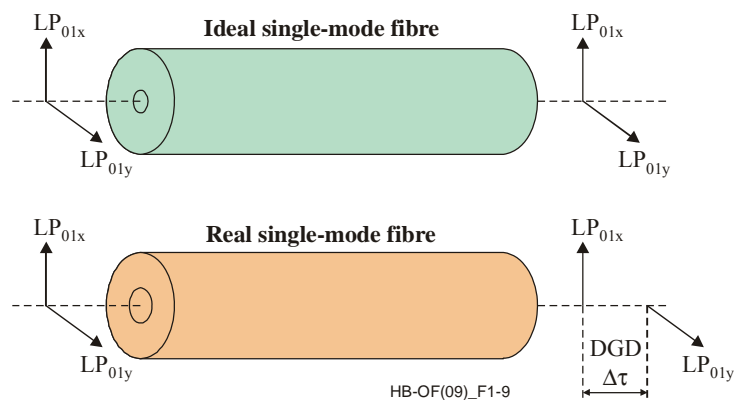

Figure 1-9 – DGD due to the two polarization modes propagating at different velocities

These two local polarization modes travel at different velocities causing a pulse spreading in digital systems (Figure 1-10). The so induced DGDs vary randomly along the fibre and in time, leading to a statistical behaviour of PMD, both in time and wavelength. At a given time, the DGD values vary randomly with wavelength. The PMD value is the average of the DGD values. While the individual values can shift from one time to another the overall distribution, hence the average is assumed to be fixed.
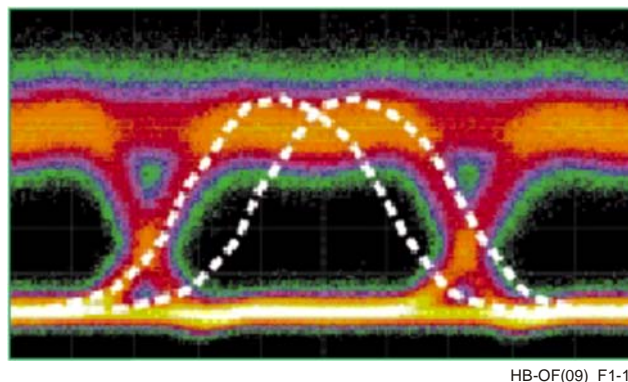

Figure 1-10 – Eye diagram of a 10 Gbit/s signal transmitted on a fibre with PMD

The *PMD coefficient* is the PMD value normalized to the measurement length. For random mode coupling, the PMD coefficient is the PMD value divided by the square root of the length ($L^{1/2}$) and is usually reported in units of ps/km$^{1/2}$.

For normal random-mode coupled fibre, the PMD distribution is ergodic, which means that the statistical distribution remains the same over time and wavelength, for a sufficiently long period or wide range.

As a consequence the mean value of all the distributions (over a long period of time, over large range of wavelengths, over a great number of concatenate sections of cable) is the same.

This also allows the assumption that measurements over a finite wavelength range are representative of other wavelength ranges or of the same wavelength range at different times over a long period of time.

For mode coupled fibres, the ergodic distribution is normally Maxwellian (see Recommendation ITU-T G.650.2) with a single parameter, which is the product of the PMD coefficient of the link and the square root of the link length (Figure 1-11).
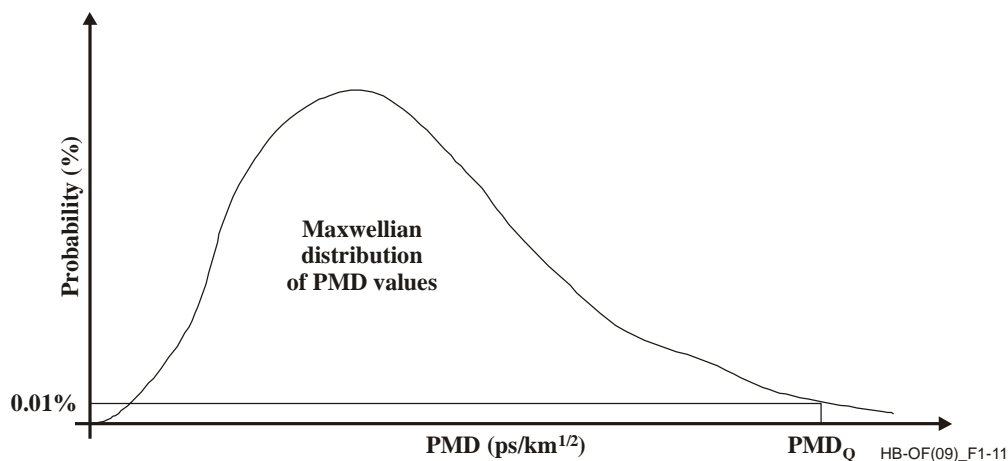

Figure 1-11 – The meaning of PMD$_Q$

A Maxwellian distribution may not be the case if there are point sources of elevated birefringence (relative to the rest of the fibre), such as a tight bend, or other phenomena that reduce the mode coupling, such as a continual reduced bend radius with fibre in tension.

Cabled fibre polarization mode dispersion is specified, therefore, on a statistical basis and not on an individual fibre basis. Moreover, the requirements pertain only to the aspect of the link calculated from cable information.

The manufacturer shall supply a PMD link design value, PMD$_Q$, that serves as a statistical upper bound for the PMD coefficient of the concatenated optical fibre cables within a defined possible link of M (generally M = 20) cable sections. The upper bound is defined in terms of a small probability level (generally 0.01%), Q, which is the probability that a concatenated PMD coefficient value exceeds PMD$_Q$.

A PMD$_Q$ specification is required only where cables are employed for systems that have the specification of the max DGD.

As said before, a probability value of 0.01% not to be exceeded is specified for the PMD, partially on the basis of obtaining equivalence with the probability that DGD exceeds a bound. As a matter of fact, the probability limit to exceed the maximum DGD value is set at $6.5 \cdot 10^{-8}$ (2 sec/year), based on various system considerations including the presence of other PMD-generating components that may be in the links.

The presence of two statistical limits, one for the PMD and another one for the DGD makes possible two approaches to the design of a transmission system:

– to take as basis the PMD_Q of the cabled fibre (e.g. when an already laid cabled fibre is used) and to choose the main system characteristics (channel bit rate, modulation format, etc.) in such a way that the DGD limit is respected;

– to take as a basis the characteristics of the system to be deployed (and therefore the DGD limit to respect) and to choose a cabled fibre which has the necessary PMD_Q .

7 Link attributes

A concatenated link usually includes a number of spliced factory lengths of optical fibre cable. The characteristics of factory lengths are given in § 6. The transmission parameters for concatenated links must take into account not only the performance of the individual cable lengths but also the statistics of concatenation.

The transmission characteristics of the factory length optical fibre cables will have a certain probability distribution which often needs to be taken into account if the most economic designs for the link are to be obtained (see Chapter 7).

Link attributes are affected by factors other than optical fibre cables, by such things as splices, connectors, and installation.

7.1 Attenuation

7.1.1 Attenuation of a link

The attenuation A of a link is given by:

$$A = \alpha L + \alpha_S x + \alpha_C y$$

where:

α : typical attenuation coefficient of the fibre cables in a link

α_S : mean splice loss

x : number of splices in a link

α_C : mean loss of line connectors

y : number of line connectors in a link (if provided)

L : link length.

A suitable margin should be allocated for future modifications of cable configurations (additional splices, extra cable lengths, ageing effects, temperature variations, etc.). The above equation does not include the signal loss of equipment connectors. The attenuation budget used in designing an actual system should account also for the statistical variations in these parameters.

7.1.2 Wavelength dependence of attenuation

The attenuation coefficient of an installed optical fibre cable is wavelength-dependent (see § 6).

Table 1-2 contains the assumed minimum and maximum attenuation coefficient values for some wavelengths used in Coarse-WDM (CWDM) systems (see Chapter 6). They are also depicted graphically in Figure 1-12 and in Figure 1-13. These values were obtained by combining measurements of the attenuation coefficient of underground and buried optical fibre cables at 1 550 nm and 1 625 nm with full spectrum measurements of uncabled fibres and with the limits specified in Recommendation ITU-T G.652 for the A-B-C-D types (see § 9.2.1).

Table 1-2 – Assumed attenuation coefficient values

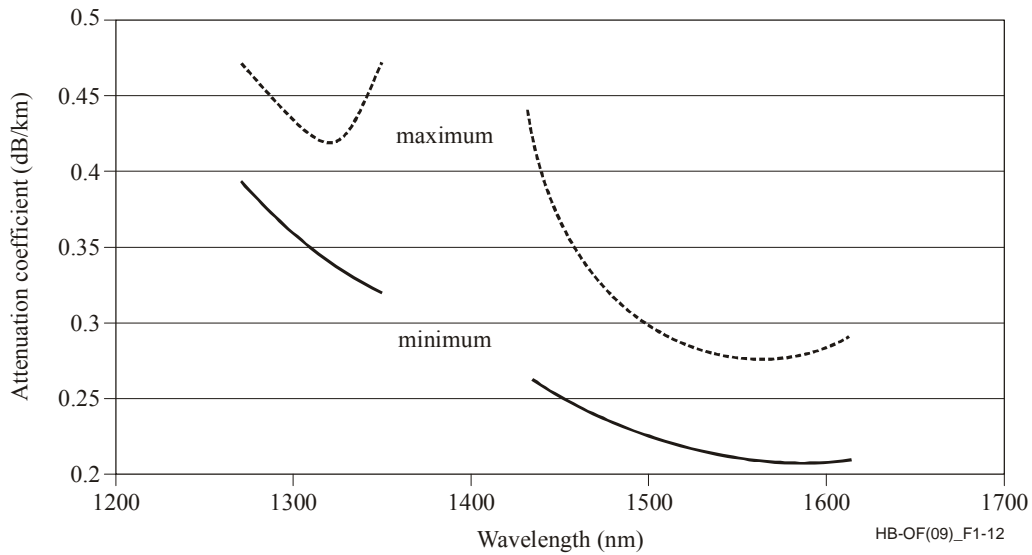| Nominal central wavelength (nm)	ITU-T G.652.A&B cable		ITU-T G.652.C&D cable	
	Minimum attenuation coefficient (dB/km)	Maximum attenuation coefficient (dB/km)	Minimum attenuation coefficient (dB/km)	Maximum attenuation coefficient (dB/km)
1 271	0.392	0.473	0.385	0.470
1 291	0.370	0.447	0.365	0.441
1 311	0.348	0.423	0.352	0.423
1 331	0.331	0.425	0.340	0.411
1 351	0.320	0.476	0.329	0.399
1 371			0.316	0.386
1 391			0.301	0.372
1 411			0.285	0.357
1 431	0.263	0.438	0.269	0.341
1 451	0.250	0.368	0.254	0.326
1 471	0.238	0.327	0.240	0.312
1 491	0.229	0.303	0.229	0.300
1 511	0.221	0.290	0.220	0.290
1 531	0.215	0.283	0.213	0.283
1 551	0.211	0.278	0.209	0.277
1 571	0.208	0.276	0.208	0.273
1 591	0.208	0.278	0.208	0.275
1 611	0.208	0.289	0.212	0.283

Figure 1-12 – Assumed attenuation coefficient values for G.652.A&B cable
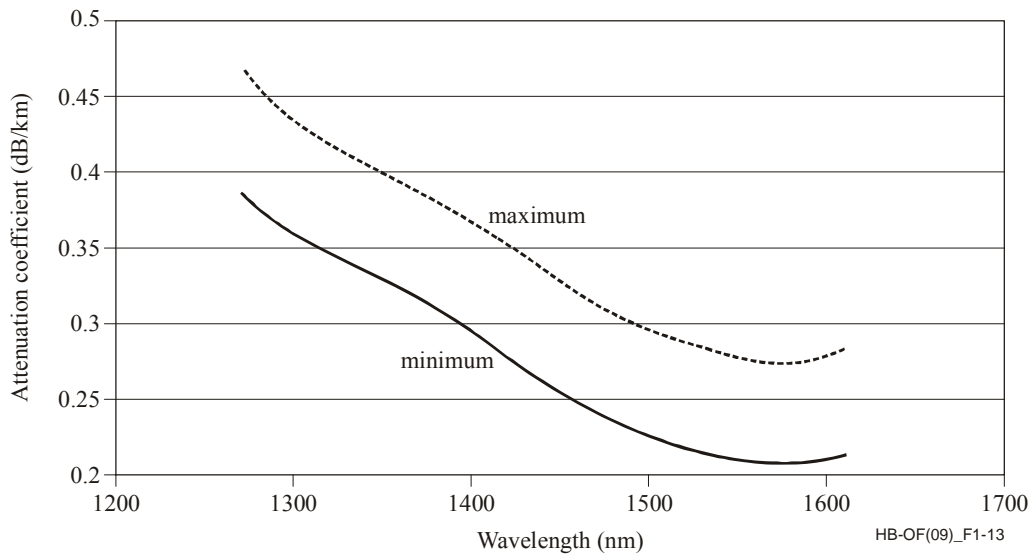
Figure 1-13 – Assumed attenuation coefficient values for ITU-T G.652.C&D cable

These attenuation coefficient values are based on the spectral results of a limited number of fibres, together with an assumption of 0.275 dB/km at 1 550 nm for the maximum attenuation coefficients and 0.210 dB/km at 1 550 nm for the minimum attenuation coefficients. Actual installed cable attenuation is statistical in nature, and these values should not be taken as specification limits on individual fibres, cable sections, or splices.

7.2 Chromatic dispersion

7.2.1 Chromatic dispersion of a link

The chromatic dispersion of a link (in ps/nm) can be calculated from the chromatic dispersion coefficients of the factory lengths, assuming a linear dependence on length, and with due regard for the signs of the coefficients.

7.2.2 Wavelength dependence of chromatic dispersion

The chromatic dispersion coefficient is wavelength dependent. Table 1-3 contains the assumed maximum chromatic dispersion coefficient values at the central wavelength (plus the maximum allowed central wavelength deviation) for some channels used in CWDM systems.

Table 1-3 – Assumed chromatic dispersion coefficient values for ITU-T G.652, ITU-T G.653 and ITU-T G.655 fibres

| Channel wavelength (nm) | Maximum dispersion coefficient (ps / nm / km) | | | | | |
| | ITU-T G.652 fibres | | ITU-T G.653 fibres | | ITU-T G.655 fibres | |
	Negative	Positive	Negative	Positive	Negative	Positive
1 291	−3.85	–	–	–	–	–
1 311	−1.85	1.60	–	–	–	–
1 331	–	3.34	–	–	–	–
1 351	–	5.02	–	–	–	–
1 371	–	6.62	–	–	–	–
1 391	–	7.97	–	–	–	–
1 411	–	9.14	–	–	–	–
1 431	–	10.31	–	–	–	–
1 451	–	11.49	–	–	–	–
1 471	–	12.68	−8.64	–	−2.99	4.78
1 491	–	13.86	−6.94	–	−1.45	5.79
1 511	–	15.06	−5.24	0.82	–	6.80
1 531	–	16.25	−3.54	1.75	–	7.82
1 551	–	17.46	−2.59	2.68	–	8.85
1 571	–	18.66	−1.66	3.71	–	9.90
1 591	–	19.87	−0.72	5.41	–	10.96
1 611	–	21.09	–	7.11	–	12.01

7.3   Differential group delay

For a link with a specific PMD coefficient, the system impairment at a specific time and wavelength depends on the DGD at that time and wavelength.

7.4   Non-linear coefficient

The effect of chromatic dispersion is interactive with the non-linear coefficient, n_2/A_{eff}, as regards system impairments induced by non-linear optical effects. Typical values vary with the implementation (see Chapter 7).

8   Test methods of single-mode optical fibres and cables

The specification of the test methods for the fibres / cables attributes is very important, because it is not possible to specify the values of the various attributes that characterize an optical fibre without having previously specified the definitions of the attributes and the test methods for measuring their values.

Test methods are classified in two categories: Reference Test Methods (RTM) and Alternative Test Methods (ATM).

A *Reference Test Method* is 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.

An *Alternative Test Method* is 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.

Both Reference Test Method and Alternative Test Methods are usually specified in Recommendation ITU-T G.650.1, and in Recommendation ITU-T G.650.2 for some parameters, and it is the intention that both the RTM and the ATMs 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.

Recommendations ITU-T G.650.1 and ITU-T G.650.2 contain definition and test methods suitable mainly for factory measurements, while Recommendation ITU-T G.650.3 outlines the tests normally done on installed optical cable sections.

Definitions and test methods contained in these three Recommendations are generally not appropriate for multimode fibre, such as that described in Recommendation ITU-T G.651.1. Here reference is made to appropriate IEC standards. Some of the test methods, when so indicated, may also be used to characterize discrete optical components, such as those described in Recommendation ITU-T G.671.

A description of the test methods is outside the scope of this Handbook; however, some general information is given in the following of this clause.

Definitions and test methods suitable mainly for factory measurements of the linear, deterministic attributes of the single-mode optical fibres and cables described in Recommendations ITU-T G.652 through ITU-TG.657 are specified in Recommendation ITU-T G.650.1.

Recommendation ITU-T G.650.1 contains RTM and ATMs for the following parameters of the optical fibres: mode field diameter, cladding diameter, core concentricity error, cladding non-circularity, cut-off wavelength, attenuation, chromatic dispersion and proof-testing.

A schematic diagram of the test apparatus is given for each test method together with the description of the main conditions for carrying out the tests. The measurement procedure and the presentation of the results are also described.

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 Recommendations ITU-T G.652 through ITU-T G.657 are specified in Recommendation ITU-T G.650.2.

Recommendation ITU-T G.650.2 contains RTM and ATMs for the PMD. Test methods for non-linear attributes are still under study. However, Appendix II of Rec. ITU-T G.650.2 gives some information on effective area (A_{eff}), non-linear coefficient (n_2/A_{eff}) and stimulated brillouin scattering.

A schematic diagram of the test apparatus is given for each test method together with the description of the main conditions for carrying out the tests. The measurement procedure and the presentation of the results are also described.

The tests normally done on installed optical fibre cable links are specified in Recommendation ITU-T G.650.3, which includes a collection of references to the main measurement methods and gives an indication of which are most suitable for installed cable sections, depending on the required inspection level needed.

Recommendation ITU-T G.650.3 contains test methods that are suited particularly to the characterization of single-mode optical fibre cable links. The methods are not intended for application to links that contain optical network elements, such as amplifiers, dispersion compensators, or passive splitters/combiners.

Recommendation ITU-T G.650.3 uses a tiered approach. The first level indicates measurements that may normally be done as part of installation. The second level indicates measurements that are normally done on exception, such as to satisfy Service Level Agreements or to verify attributes of older links that may be used at high bit rates.

Test methods for characteristics of optical fibre cable links specified in Recommendation ITU-T G.650.3 include attenuation, splice loss, fibre uniformity, PMD and chromatic dispersion.

9   Optical fibre types specified by ITU-T

9.1   Multimode optical fibres

9.1.1   A 50/125 μm multimode graded index optical fibre cable

The characteristics of a multimode graded index optical fibre cable were specified in Recommendation ITU-T G.651, originally published in 1984 and deleted in 2008. Recommendation ITU-T G.651 covered the geometrical and transmissive properties of multimode fibres having a 50 μm nominal core diameter and a 125 μm nominal cladding diameter.

That Recommendation was developed during the infancy of optical fibre solutions for publicly switched networks. At that time (pre-1984), these multimode fibres were considered as the only practical solution for transmission distances in the tens of kilometres and bit rates of up to 40 Mbit/s. Single-mode fibres, which became available shortly after the publication of ITU-T G.651, have almost completely replaced multimode fibres in the publicly switched networks.

Today, multimode fibres continue to be widely used in premises cabling applications such as Ethernet in lengths from 300 to 2 000 m, depending on bit rate. With a change in the applications, the multimode fibre definitions, requirements, and measurements evolved away from the original ITU-T G.651 and were moved to the modern ITU equivalent, Recommendation ITU-T G.651.1.

Recommendation ITU-T G.651.1, *Characteristics of a 50/125 μm multimode graded index optical fibre cable for the optical access network*, provides specifications for a 50/125 μm multimode graded index optical fibre cable suitable to be used in the 850 nm region or in the 1 300 nm region or alternatively may be used in both wavelength regions simultaneously. This Recommendation contains the recommended values for both the fibre and cable attributes.

The applications of this fibre are in specific environments of the optical access network. These environments are multi-tenant building sub-networks in which broadband services have to be delivered to individual apartments. This multimode fibre supports the cost-effective use of 1 Gbit/s Ethernet systems over link lengths up to 550 m, usually based upon the use of 850 nm transceivers.

Quite a large percentage of all customers in the world are living in these buildings. Due to the high connection density and the short distribution cable lengths, cost-effective high capacity optical networks can be designed and installed by making use of 50/125 μm graded-index multimode fibres.

The effective use of this network type has been shown by its extended and experienced use for datacom systems in enterprise buildings with system bit-rates ranging from 10 Mbit/s up to 10 Gbit/s. This use is supported by a large series of IEEE system standards and IEC fibre and cable standards, which are used as the main references in Recommendation ITU-T G.651.1.

9.2   Single-mode optical fibres

9.2.1   The ITU-T first single-mode optical fibre and cable

The first single-mode optical fibre was specified in Recommendation ITU-T G.652, *Characteristics of a single-mode optical fibre and cable*, and for this reason, the ITU-T G.652 fibres are often called, "standard single-mode fibres". These fibres were the first to be widely deployed in the public network and they represent a large majority of fibres that have been installed. The agreements that led to the first publication of Recommendation ITU-T G.652 formed a key foundation to the modern optical networks that are the basis of all modern telecommunications.

Recommendation ITU-T G.652 describes the geometrical, mechanical, and transmission attributes of a single-mode optical fibre and cable which has zero-dispersion wavelength around 1 310 nm. This fibre was originally optimized for use in the 1 310 nm wavelength region, but can also be used in the 1 550 nm region. Recommendation ITU-T G.652 was first created in 1984; several revisions have been intended to maintain the continuing commercial success of this fibre in the evolving world of high-performance optical transmission systems.

Over the years, parameters have been added to Recommendation ITU-T G.652 and the requirements have been made more stringent to meet the changes in market and technological demands, and in manufacturing capability. An example is the addition of a requirement for attenuation at 1 550 nm in 1988. In that year, the chromatic dispersion parameters and requirements were also defined.

Some other examples include the addition of low water peak fibres (LWP) with negligible sensitivity to hydrogen exposure and the addition of requirements for PMD. However at the advent of these new capabilities and perceived needs, there was a consensus that some applications would need these attributes for advanced technologies, bit rates, and transmission distances; however, there were also applications that would not need these capabilities. Therefore, some options had to be maintained.

For this reason, it was agreed to create different categories of ITU-T G.652 fibres. At the present time there are four categories, A, B, C, and D, which are distinguished on the PMD_Q link design value specification and whether the fibre is LWP or not, i.e. water peak is specified (LWP) or it is not specified (WPNS), as shown in Table 1-4.

Table 1-4 – ITU-T G.652 fibre categories

Category	Maximum PMD_Q $(ps/km^{1/2})$	Water Peak
A	0.5	WPNS
B	0.2	WPNS
C	0.5	LWP
D	0.2	LWP

A non-normative Appendix in Rec. ITU-T G.652 gives representative values of attenuation and chromatic dispersion, which can be taken as the basis for the design of concatenated optical fibre links in accordance with the guidelines outlined in Supplement 39 to the ITU-T G-series Recommendations. The same Appendix gives an indication of the maximum link length at various channel bit rates allowed by different values of Polarization Mode Dispersion (PMD_Q).

Category A of ITU-T G.657 (see § 9.2.6) is aligned with all the ITU-T G.652.D values, but has more stringent bend loss requirements.

9.2.2 A dispersion-shifted single-mode optical fibre and cable

The characteristics of a dispersion-shifted single-mode optical fibre and cable are described in Recommendation ITU-T G.653. This fibre has a nominal zero-dispersion wavelength close to 1 550 nm and a dispersion coefficient that is monotonically increasing with wavelength. This fibre was initially developed for use in single-channel high bit rate and long distance transmission in the 1 550 nm region (where the attenuation coefficient is smallest) by shifting the zero-dispersion wavelength of the ITU-T G.652 fibre to around 1 550 nm. This fibre is optimized for use in the 1 550 nm region, but may also be used at around 1 310 nm subject to the constraints outlined in the Recommendation. Some provisions are made to support transmission at higher wavelengths up to 1 625 nm and lower wavelengths down to 1 460 nm.

This was the second Recommendation for single-mode fibre and cable, and it was first created in 1988. The current version contains two categories, A and B, that are distinguished on the PMD_Q link design value specification, the description of the chromatic dispersion coefficient, the geometrical parameters and the macrobending loss specifications.

ITU-T G.653.A fibre is the base category for a dispersion-shifted single-mode optical fibre and cable, and retains the original "box-type" specification for the dispersion coefficient. The zero-dispersion wavelength is within the operating wavelength range from 1 525 nm to 1 575 nm, so that it performs very well for single-channel systems (e.g. ITU-T G.957, ITU-T G.691 and ITU-T G.693 systems), but non-linear effects are deleterious in dense wavelength division multiplexing (DWDM) systems with an equal channel spacing in the 1 550 nm wavelength region. However, this category is also suitable for multichannel systems (e.g. ITU-T G.692 and ITU-T G.977 systems) with unequal channel spacing in the 1 550 nm wavelength region (for more detail on unequal channel spacing see Recommendation ITU-T G.692). The ITU-T G.653.A fibre is used for multichannel systems with equal channel spacing within the operating wavelength range from 1 565 nm to 1 625 nm where the chromatic dispersion has non-zero values (e.g. ITU-T G.698.1 and ITU-T G.698.2 systems).

Many submarine applications can utilize this category. For some submarine applications, the full optimization can lead to choosing different limits than are found here. One example could be to allow cable cut-off wavelength to values as high as 1 500 nm.

ITU-T G.653.B fibre attributes are similar to those of ITU-T G.653.A fibre, but the more stringent PMD requirement allows STM-64 systems to lengths longer than 400 km and ITU-T G.959.1 NRZ 40G applications. This category defines the chromatic dispersion coefficient requirements as a pair of bounding curves vs. wavelength for wavelengths from 1 460 nm to 1 625 nm. This category may support coarse wavelength division multiplexing applications which do not have significant non-linear impairments.

9.2.3   A cut-off shifted single-mode optical fibre and cable

The characteristics of a cut-off shifted single-mode optical fibre and cable are specified in Recommendation ITU-T G.654, which describes the geometrical, mechanical and transmission attributes of a single mode optical fibre and cable which has its zero-dispersion wavelength around 1 300 nm and which is loss-minimized and cut-off wavelength shifted to the 1 550 nm wavelength region.

At first, this Recommendation was created as "Characteristics of a 1 550 nm wavelength loss-minimized single-mode optical fibre cable" in 1988, for the purpose of submarine cable system use. In 1997, the name of this Recommendation was changed to "Characteristics of a cut-off shifted single-mode optical fibre and cable", in order to make clearer the features of this fibre.

The main features of the fibre described by Recommendation ITU-T G.654 are its longer cut-off wavelength and lower attenuation coefficient at 1 550 nm compared to other single-mode optical fibres. The longer cut-off wavelength can allow lower macrobending loss fibre design; hence, it is advantageous to submarine cables, which require lower attenuation. The lowest values of attenuation coefficient depend on fabrication process, fibre composition and design, and cable design. Values of 0.15 to 0.19 dB/km in the 1 550 nm region have been achieved. These features are suitable for long-haul transmission in the 1 530-1 625 nm region.

The current version of this Recommendation contains three categories: A, B and C.

Category A is the base category that, considering its very low attenuation, can be used for long-distance digital transmission applications such as long-haul terrestrial line systems and submarine cable systems using optical amplifiers. This category is suitable for the systems specified in Recommendations ITU-T G.691, ITU-T G.692, ITU-T G.957 and ITU-T G.977 in the 1 550 nm wavelength region.

Category B has a larger upper limit of MFD than Category A and reduced PMD requirement. This category is suitable for the systems described in the above-quoted Recommendations and for the ITU-T G.959.1 long-haul applications in the 1 550 nm wavelength region. This category B can also be applied to longer distance and larger capacity WDM repeaterless submarine systems with remotely pumped optical amplifier, as discussed in Recommendation ITU-T G.973 and submarine systems with optical amplifiers, as discussed in Recommendation ITU-T G.977.

Category C is similar to Category A, but the reduced PMD requirement also supports the highest bit-rate and long-haul applications among those described in ITU-T G.959.1.

9.2.4   A non-zero dispersion-shifted single-mode optical fibre and cable

The characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable are described in Recommendation ITU-T G.655. This Recommendation specifies the geometrical, mechanical, and transmission attributes of a single-mode optical fibre which has the absolute value of the chromatic dispersion coefficient greater than some non-zero value throughout the wavelength range from 1 530 nm to 1 565 nm. This dispersion reduces the growth of non-linear effects which are particularly deleterious in dense wavelength division multiplexing systems.

This Recommendation was first created in 1996 and was initially developed following the creation of the dispersion-shifted fibres (see Recommendation ITU-T G.653) and the advent of dense wavelength division multiplexing (DWDM) in long distance, optically amplified and dispersion compensated networks. As

indicated above, allowance for zero or low values of dispersion in the operating window of these systems allows the growth of non-linear effects, such as four-wave mixing. For this reason, the zero-dispersion wavelength had to be moved out of the operating window.

In the initial version of this Recommendation, the dispersion requirements were expressed as a "box specification", in which the absolute value of the dispersion coefficient had to be restricted to a range starting with a positive value and bound by another larger value over a wavelength range believed to encompass the operating window of the DWDM systems. Many possible technical tradeoffs and developments were anticipated, so the initial ranges were allowed to be large enough to allow evolution. Examples of such tradeoffs include:

i) degree of dispersion compensation, amplification, and consequent optical noise;

ii) DWDM channel density and range;

iii) channel power levels;

iv) the possibility of Raman amplification;

v) the possibility of dispersion management.

Despite the looseness of the primary chromatic dispersion coefficient requirement and the mix of system strategies, large volumes of ITU-T G.655 fibres were deployed in the longer distance networks that emerged in the late 1990's and early 2000's. These fibres had, depending on the fibre manufacturer, differently detailed, but more restrictive, limits on the chromatic dispersion coefficient, depending on the relevant technical strategy of their customers. As an example, in 2000, the second edition adapted a new Table B for which the maximum absolute value of dispersion was allowed to reach 10 ps/(nm.km) over the 1 530-1 565 nm band (vs. 6 ps/(nm.km) in Table A), introducing the medium-dispersion type ITU-T G.655 fibre.

In 2005, following the bursting of the "telecommunications bubble", two main aspects emerged, which changed the standardization strategy for ITU-T G.655 fibres:

i) the customers and network providers demanded more specific values for the chromatic dispersion coefficient vs. wavelength. The "box specification" was not sufficiently useful;

ii) two main varieties of these fibres were seen in the market: one with lower dispersion coefficient and another with medium dispersion coefficient, but much lower than ITU-T G.652 fibres.

To address these aspects, surveys of all the participating fibre manufacturers were conducted. The results of these surveys were used to define the chromatic dispersion coefficient limits vs. wavelength for two new categories that are defined in Tables D and E of Recommendation ITU-T G.655, which have been included in the present version of Recommendation ITU-T G.655. They distinguish the two main families of ITU-T G.655 fibres that are supported by multiple vendors. Both of these categories limit the chromatic dispersion coefficient by a pair of bounding curves vs. wavelength for the range of 1 460 nm to 1 625 nm. Although the dispersion can change sign at wavelengths less than 1 530 nm, the inclusion of these lower wavelengths is intended to provide information to support CWDM applications which do not have significant non-linear impairments, at channels from 1 471 nm and higher.

Tables A, B, and C have not been changed. Tables A and B are not included in the 2006 version of this Recommendation, but are in the 2003 edition. Table C, based on a box specification that allows positive and negative dispersion coefficients for possible use in dispersion managed systems, was retained.

9.2.5 A fibre and cable with non-zero dispersion for wideband optical transport

The characteristics of a fibre and cable with non-zero dispersion for wideband optical transport are specified in Recommendation ITU-T G.656. The specification is for a single-mode fibre and cable with chromatic dispersion that is greater than some non-zero value throughout the wavelength range of 1 460-1 625 nm.

In the current development of lightwave systems, one direction of evolution is towards increasing the capacity transmitted on an optical fibre. One of the solutions is by deploying the optical channels not only in the C-band, but also in the short wavelength S-band (1460-1530 nm) and in the long wavelength L-band (1 565-1 625 nm). This type of fibre can be utilized for both CWDM and DWDM systems throughout the wide wavelength region between 1 460 and 1 625 nm.

Recommendation ITU-T G.656 describes the geometrical, mechanical, and transmission attributes of the fibre and cable. The chromatic dispersion of the fibre reduces the growth of non-linear effects which are particularly deleterious in DWDM systems over a wider wavelength range than the fibre described in Recommendation ITU-T G.655.

Recommendation ITU-T G.656 has a single category of the fibre and cable. The category limits the chromatic dispersion coefficient by a pair of bounding curves vs. wavelength for the range of 1 460 nm to 1 625 nm, which provides information to support CWDM applications such as those described in Recommendation ITU-T G.695 and DWDM applications such as those described in Recommendations ITU-T G.692, ITU-T G.696.1, ITU-T G.698.1, ITU-T G.698.2 and ITU-T G.959.1. The PMD requirement of the fibre and cable allows operation of STM-64 systems to lengths of up to 2 000 km, depending on other system elements.

9.2.6   A bending loss insensitive single mode optical fibre and cable for the access network

The characteristics of a bending loss insensitive single mode optical fibre and cable for the access network are specified in Recommendation ITU-T G.657.

Worldwide, technologies for broadband access networks are advancing rapidly. Among these, the technology applying single mode fibre provides for a high-capacity transmission medium that can answer the growing demand for broadband services.

The experience with the installation and operation of single mode fibre and cable based networks is extensive and ITU-T G.652 fibre characteristics have been adapted to this experience. Nevertheless, the specific use in an optical access network puts different demands on the fibre and cable. Due to the dense distribution and drop-cable network, the limited space and the many manipulations in this part of the network, fibre and cable requirements may be optimized for lower bending sensitivity compared to that of cabled fibre used in a general transport network.

It is the aim of Recommendation ITU-T G.657 to support this bending optimization by recommending different attribute values and by recommending other classes of single mode fibre types.

Recommendation ITU-T G.657 describes two categories (A and B) of single-mode optical fibre cable that are suitable for use in the access networks, including inside buildings at the end of these networks.

Category A fibres are suitable to be used in the O, E, S, C and L-band, i.e. throughout the 1 260 to 1 625 nm range (See Chapter 6). Fibres and requirements in this category are a subset of ITU-T G.652.D fibres and have the same transmission and interconnection properties. The main improvements are lower bending loss and tighter dimensional specifications, both for improved connectivity.

Category B fibres are suitable for transmission at 1 310, 1 550 and 1 625 nm for restricted distances that are associated with in-building transport of signals. These fibres may have different splicing and connection properties than ITU-T G.652 fibres, but can be used at very low bend radii because of further improved bending loss.

The improved macrobending behaviour of ITU-T G.657 fibres for use in broadband optical access networks, supports small volume fibre management systems and low radius mounting in telecom offices and customer premises in apartment buildings and single dwelling houses.